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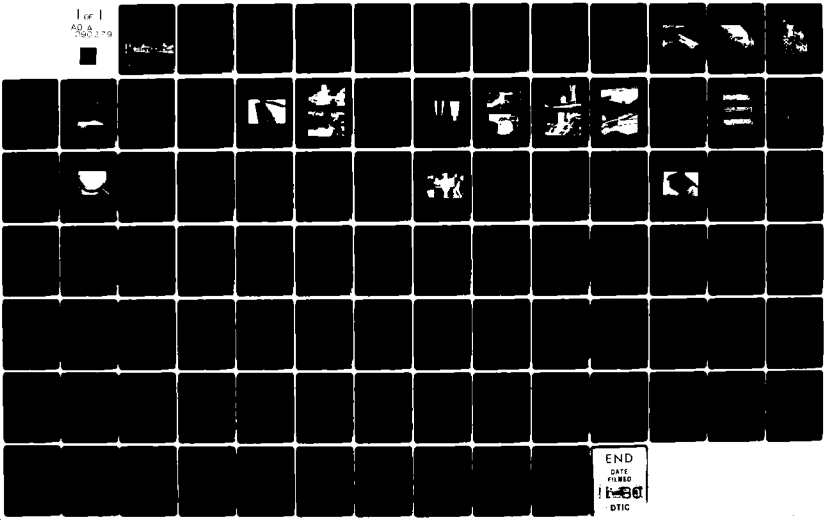

MISCELLANEOUS PAPER SL-80-10

CONSTRUCTION OF TREMIE CONCRETE CUTOFF WALL, WOLF CREEK DAM, KENTUCKY

by

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Final Report

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Significant leakage was occurring at a Corps of Engineers dam. The cause of the leakage was postulated to be flow through the dam's cutoff trench or through solution cavities beneath the dam or through both. The repair technique selected was to construct a concrete cutoff wall through the earth-fill portion of the dam into the rock foundation using a modification of the diaphragm wall technique often used in foundation construction. Concrete was placed by tremie

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20. ABSTRACT (Continued).

to construct the individual elements making up the wall. The construction methods, equipment, and materials are described in this report.

The report emphasizes the effort to determine the cause of isolated areas of heterogeneities such as honeycomb and laitance which were found in the completed wall. The apparent cause was a combination of segregation occurring during the fall of the concrete through the tremie, the small diameter of the wall elements, the smooth walls of the casings being used for the elements, and the rapid rate of concrete placement. It is believed that these last three factors inhibited concrete remixing within the wall elements leading to the heterogeneities noted.

Since the problems were confined to cased elements, no detrimental effects on the cutoff wall are anticipated. Overall, the procedure has proved to be an effective cure for the leakage at the structure.

The problems identified also have bearing on other types of deep, confined tremie concrete placements such as cast-in-place piles or piers or the filling of precast concrete elements.

PREFACE

This report was prepared at the Structures Laboratory (SL) of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Office, Chief of Engineers (OCE), U. S. Army, as a part of Civil Works Investigation Work Unit 31553, Maintenance and Preservation of Civil Works Structures. Mr. James A. Rhodes and Mr. Fred Anderson of the Structures Branch (DAEN-CWE-DC), Engineering Division, OCE, served as technical monitors.

The study was conducted under the general supervision of Mr. Bryant Mather, Chief, SL, and Mr. John Scanlon, Chief, Concrete Technology Division, SL, and under the direct supervision of Mr. James E. McDonald, Chief, Evaluation and Montioring Group, SL. MAJ Terence C. Holland, Structures Branch, SL, prepared this report with the assistance of Mr. Joseph R. Turner, Huntington District, who was Resident Engineer during the majority of the construction. The assistance of Mr. Duane Dyer, Nashville District, initially Assistant and later Resident Engineer, is appreciated.

The work covered by this report was initiated by MAJ Holland under a Federal Highway Administration (FHWA) grant to the University of California, Berkeley. Professor Ben C. Gerwick oversaw the work there, and his comments and assistance on this work are also appreciated. Additional time and funding from the WES allowed the present report to cover several areas not completely covered in the FHWA effort.

Commanders and Directors of the WES during this study and the preparation and publication of this report were COL John L. Cannon and COL Nelson P. Conover, CE. Technical Director was Mr. Fred R. Brown.

CONTENTS

CONVERSION FACTORS, INCH-POUND TO METRIC (SI) UNITS OF MEASUREMENT

Inch-pound units of measurement in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acre-feet	1233.489	cubic metres
cubic feet	0.02831685	cubic metres
cubic feet per second	0.02831685	cubic metres per second
cubic yards	0.7645549	cubic metres
cubic yards per hour	0.7645549	cubic metres per hour
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
feet per hour	0.3048	metres per hour
feet per second	0.3048	metres per second
inches	25.4	millimetres
miles (U. S. statute)	1.609344	kilometres
ounces (U. S. liquid) per cubic yard	38.6807	cubic centimetres per cubic metre
pounds (force) per foot	14.59390	newtons per metre
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6894.757	pascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.05933	kilograms per cubic metre
square inches	0.00064516	square metres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

CONSTRUCTION OF TREMIE CONCRETE CUTOFF WALL
WOLF CREEK DAM, KENTUCKY

PART I: INTRODUCTION

1. The analysis described in this report was undertaken to identify and correct the cause or causes of limited but persistent problems with the quality of tremie concrete being placed at Wolf Creek Dam. Since this project represented one of the first cases where tremie concrete was used as it was here, since this type of construction may be expected to reoccur within the Corps, and due to the interest expressed in this project when it was described by Mr. Joseph R. Turner at the Corps' General Concrete Conference,* decision was made to publish this information as part of the WES investigation of Maintenance and Preservation of Civil Works Structures.

Description of Dam

2. Wolf Creek Dam is a multipurpose structure (power generation, flood control, recreation) located on the Cumberland River near Jamestown, Kentucky. It lies in an area of karst topography approximately sixty miles** from Mammoth Cave. Lake Cumberland, impounded by the dam, is the largest man-made lake east of the Mississippi River. At its maximum pool, the lake contains 6,100,000 acre-ft of water.

3. Construction of the dam was begun in 1941, but work was discontinued for 3 years during World War II. The work accomplished prior to the war was mainly site preparation and construction of a cutoff trench under the earth-fill portion of the dam. The project was completed for full beneficial use in 1952.

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* U. S. Army Corps of Engineers, General Concrete Conference, 14-18 May 1979, Pittsburgh, Pa.

** A table of factors for converting inch-pound units of measurement to metric (SI) units is presented on page 3.

4. The dam consists of an earth-fill section 3,940 ft long and a concrete gravity section 1,796 ft long. The maximum height of the embankment section is 258 ft. The concrete section includes a gated spillway with 10 radial gates having a rated discharge of 553,000 cfs. The power plant has an installed capacity of 270,000 kw in six units. An overall view of the dam is shown in Figure 1.

Description of Problem

5. In October 1967 a muddy flow appeared in the tailrace of the dam. In March 1968 a sinkhole appeared on the toe of the dam near the switchyard. An investigation of this hole showed it was connected to a solution cavity. In April 1968 a second sinkhole appeared near the first. Dye placed in this hole appeared in the tailrace where the muddy flow had originally been seen. As a result of these occurrences, an emergency grouting program was undertaken. This program resulted in placement of 260,000 cu ft of grout but provided no assurance of completely resolving the problem.

6. After extensive site investigations, the Corps of Engineers and its consultants theorized that the flow was either through the original cutoff trench or through a combination of the cutoff trench and a series of solution features. (It should be noted that the original cutoff trench is only about 10 feet wide at its narrowest point. Photographs (Figure 2) indicate that the rock in the walls of the trench is fractured and jointed and in many cases the walls are vertical or even overhang the excavated portion.) Additional details of the problem, the extensive coring program, and the emergency grouting may be found in the papers by Dunn (1977) and Fetzer (1979a).

7. The repair procedure recommended and selected was to construct a positive cutoff wall through the earth-fill portion reaching into sound rock below the dam. A second wall was to be constructed in the area of the switchyard to protect that area from fluctuations of the tailwater.

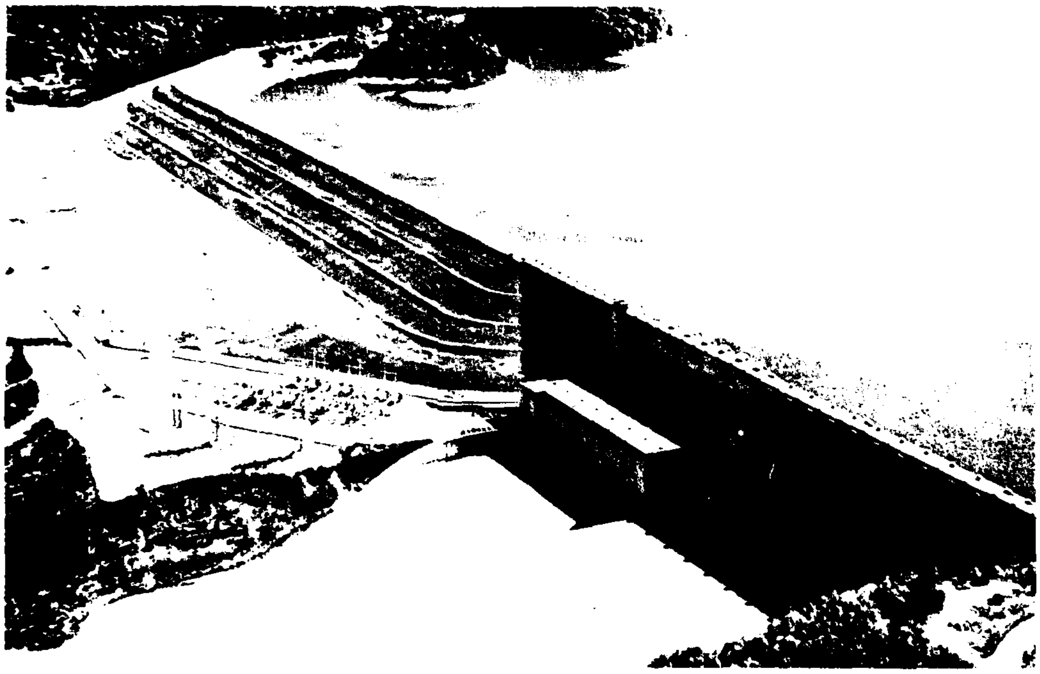


Figure 1. Overall view of Wolf Creek Dam

a. Note overhang left in place

Figure 2. Construction of cutoff trench (Continued)

b. Note width of trench

Figure 2. (Concluded)

Repair Procedures

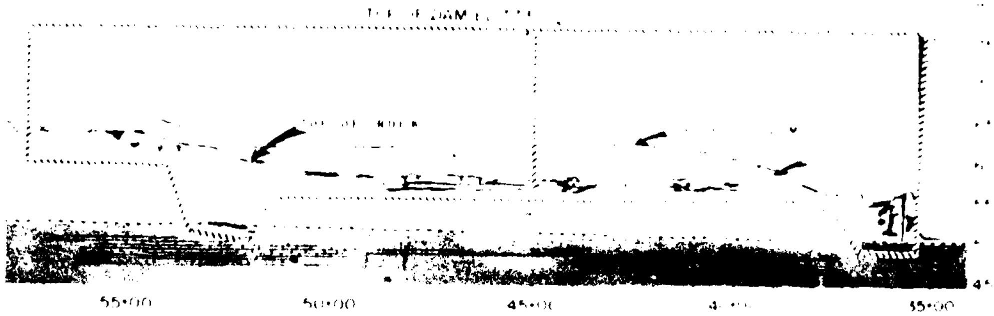
8. The construction procedure selected to install the cutoff walls was a modification of the slurry or diaphragm wall technique often used on foundation excavations. General descriptions of the slurry wall technique have been published (Anonymous 1973 and Nash 1974). Additional details of the work at Wolf Creek have also been published (Couch and Ressi de Cervia 1979, Anonymous 1976, Dunn 1977, and Fetzer 1979a), but none of these reports has dealt at length with the tremie concrete placements.

9. The Wolf Creek embankment wall is 2240 ft long and has a maximum depth of 278 ft. A profile and section view of the wall are shown in Figure 3. Due to concern over the stability of the dam during construction, the wall was constructed of alternating primary (cased, 26-in. diameter on 4.5-ft centers) and secondary (uncased) elements rather than of panels as is frequently done on slurry wall foundation projects. Figure 4 shows a schematic view of these two types of wall elements. A total of 1256 elements were placed to construct both of the cutoff walls at a total contract cost of $96.4 million. These elements were broken down as follows:

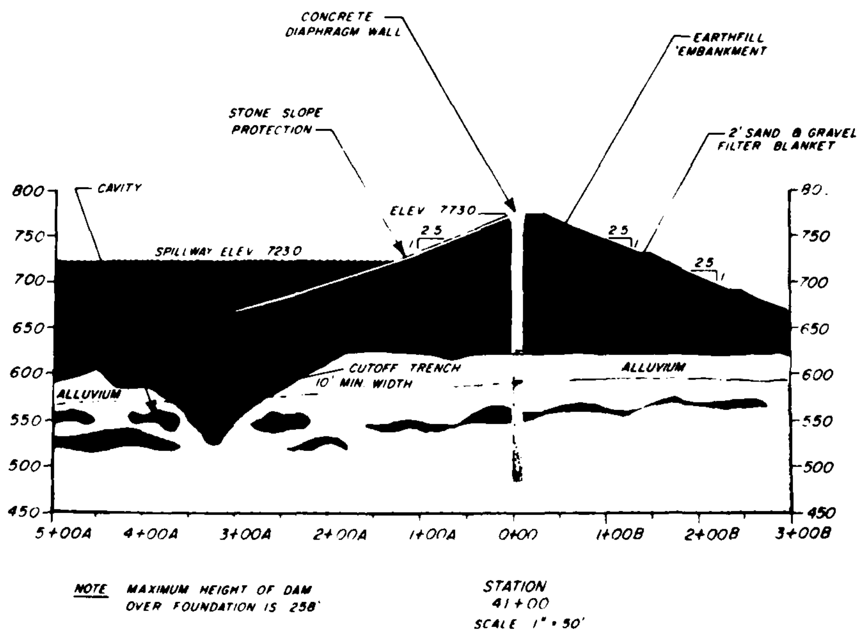
Over 250 ft deep:	158
200 to 250 ft deep:	666
150 to 200 ft deep:	168
90 to 150 ft deep:	174
Less than 90 ft deep:	90

10. The cutoff wall in the switchyard area was much shallower (100 ft) than that in the embankment. No difficulties were encountered during construction of the swit·hyard wall and very limited coring showed excellent concrete in a primary and a secondary element. Since nothing unusual was encountered during this portion of the work, the remainder of this report deals only with the construction of the embankment wall.

11. Due to the size of the project, the contract was broken into two approximately equal packages and only prequalified contractors were



a. Profile - concrete section is at right edge



b. Section

Figure 3. Profile and section views of dam and cutoff wall

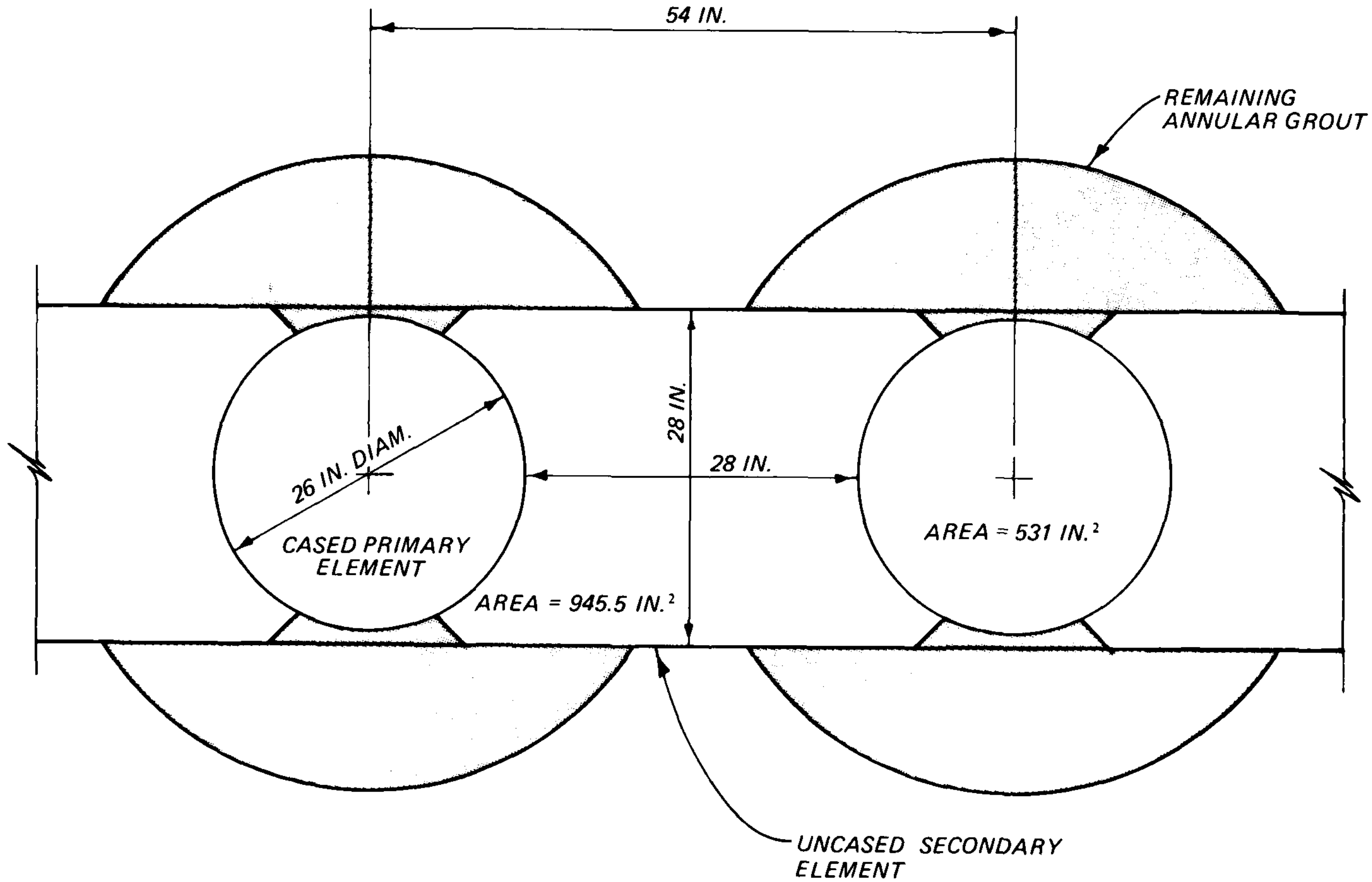


Figure 4. Schematic of tremie placed cutoff wall

allowed to bid. Both portions of the contract were awarded to ICOS Corporation of America, a pioneering firm in the field of slurry wall construction.

Site preparation

12. Since the crest width of the dam is only 32 ft, the contractor constructed a work platform 170 ft wide inside parallel walls of sheet piling (Figure 5). Actual excavation took place in a concrete lined starter trench which was constructed along the axis of the wall. Additionally, a trench parallel to the starter trench provided utilities, fresh bentonite supply, and used bentonite return. A bentonite slurry mixing and pumping plant was assembled on the top of the dam while a bentonite recovery operation was established at the toe of the dam.

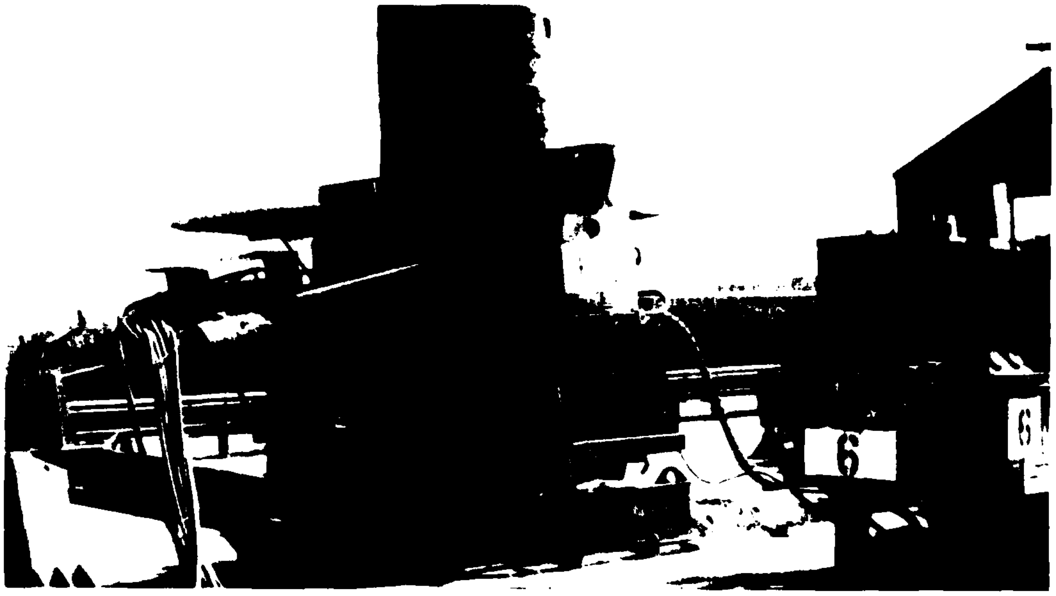
Primary elements

13. Initially, a 53-in.-diam uncased hole was excavated with a specially designed clamshell to a depth of approximately 76 ft. In all but a few instances this initial excavation was done without bentonite slurry to hold the hole open. Below the 76-ft depth, excavation was accomplished through a bentonite slurry and the hole was cased. A 47-in.-diam casing was used to a depth of 142 ft. From there to the top of rock, a 41-in.-diam casing was used. All casing was designed with joints which were flush inside and outside for ease in placing and removing. Much of the excavation and casing handling equipment was specially designed by the contractor for this project (Figure 6).

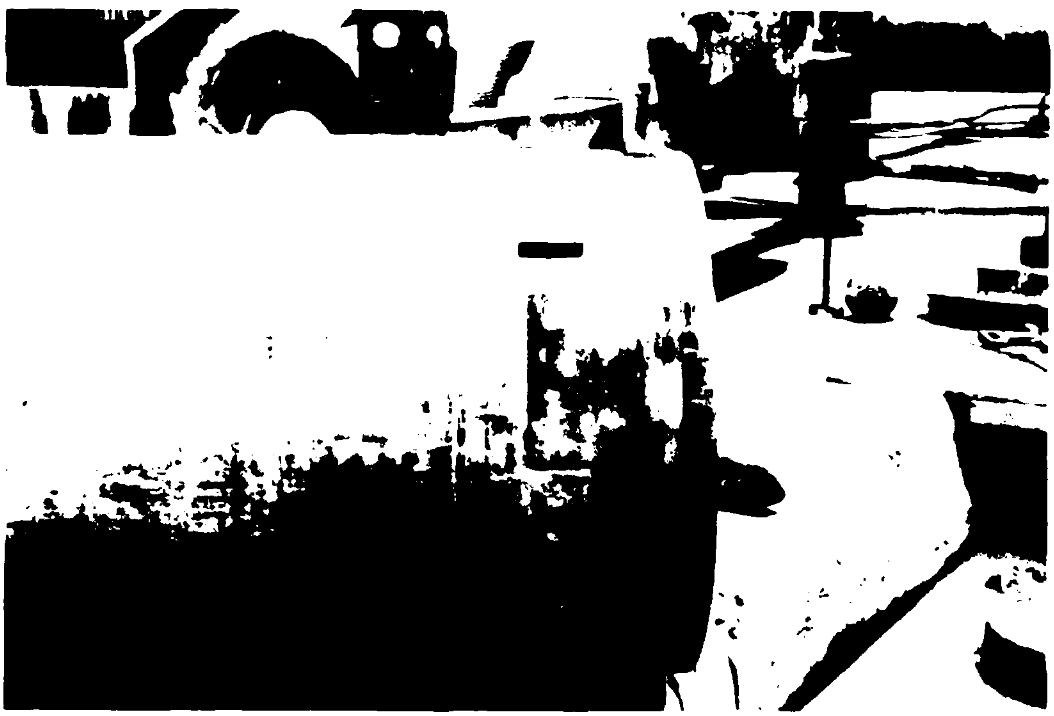
14. When rock was reached, a rock drill was used to drill a 36-in.-diam hole to the design bottom of the wall. Then, an NX core hole was taken 25 ft deeper into the rock. This hole was pressure tested and, if satisfactory, was filled with grout. If the rock failed the pressure test or weathered core was recovered, the 36-in.-diam hole was continued deeper. The bottom of the wall was founded at least 10 ft below any sign of weathered rock.

15. Once the hole was founded in sound rock, the 26-in.-diam permanent casing was placed. This casing was filled with water to keep it in place. After the permanent casing was in place, the annular space between the permanent and excavation casings was filled with grout as

Figure 5. View of contractor's platform. This photo was taken during the first phase of the project adjacent to the concrete section of the dam



a. Casing handling machine. This machine both rotates and applies vertical force for casing installation or removal



b. Details of casing joint

Figure 6. Casing for primary elements

the 41- and 47-in.-diam casings were removed. The annular space grout was allowed to set 10 days before an element was filled with tremie concrete. Figure 7 shows a schematic of a completed primary element.

16. To begin the tremie concrete filling process, enough bentonite slurry was placed through the tremie pipe into the casing to displace the lower 20 ft of water. The purpose of this bentonite was to lubricate the inside walls of the casing during tremie concrete placement. Concrete was batched and mixed at a plant near the dam and transported to the tremie site by truck mixers. Two unusual items concerning the tremie placement are worthy of noting here. First, the tremie hopper was equipped with a breathing tube which allowed air to escape during concreting. Almost no air was seen bubbling to the surface as is common on most tremie placements (Figure 8). Second, the contractor developed a novel technique for supporting the tremie pipe (Figure 9).

Secondary elements

17. Construction of a secondary element followed completion of two adjacent primary elements. The overall construction sequence was planned to allow an adequate curing period for the concrete in the primary elements before work was started on the intervening secondary element.

18. The construction process for secondary elements was identical to that described above with the following exceptions: First, the excavation was partially accomplished using a clamshell which followed the walls of the adjacent primary elements. This procedure removed the annular grout on one side of the primary elements and ensured a concrete to casing bond once the secondary elements were concreted. A variety of drills and other custom designed equipment were also used during excavation of the secondary elements (Figure 10). The second difference was that the secondary elements were excavated through bentonite slurry for their entire depth since they were not cased. Once the secondary elements were socketed into rock, tremie concrete was placed to fill the elements and displace the slurry.

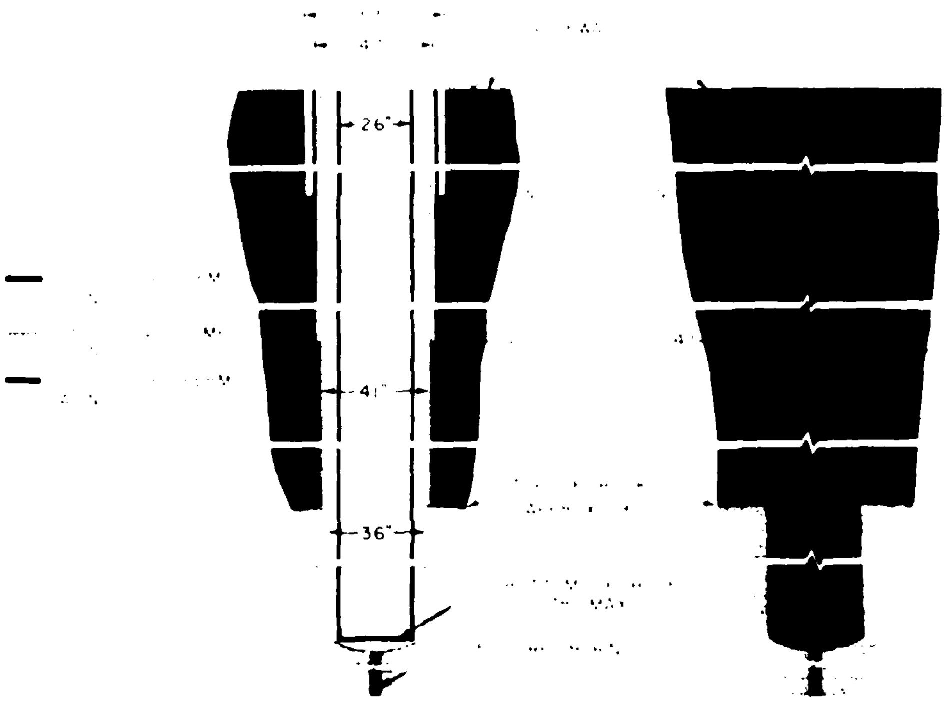
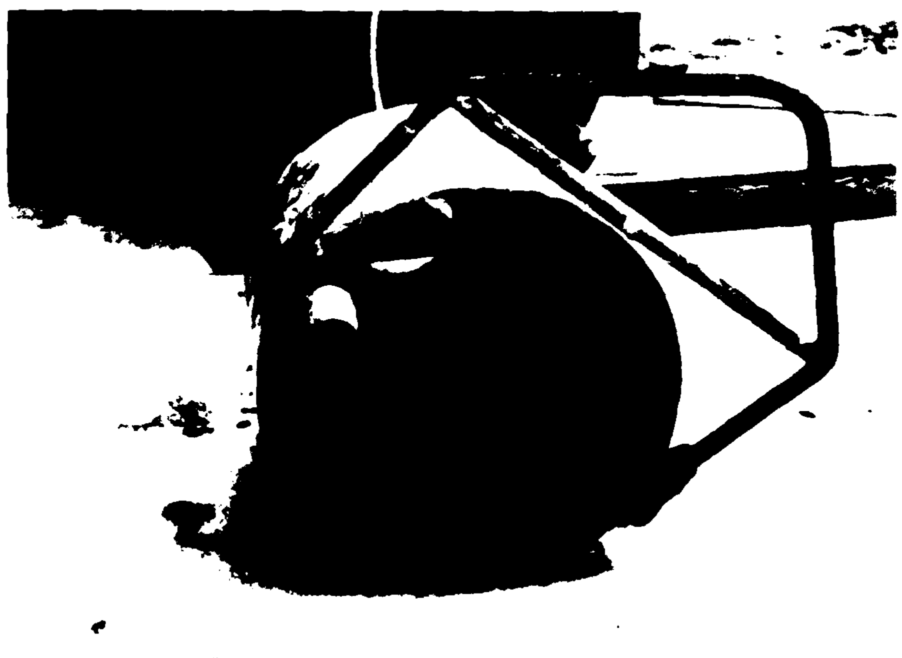


Figure 7. Schematic of completed primary element

a. Breather tube extends only a short distance below hopper



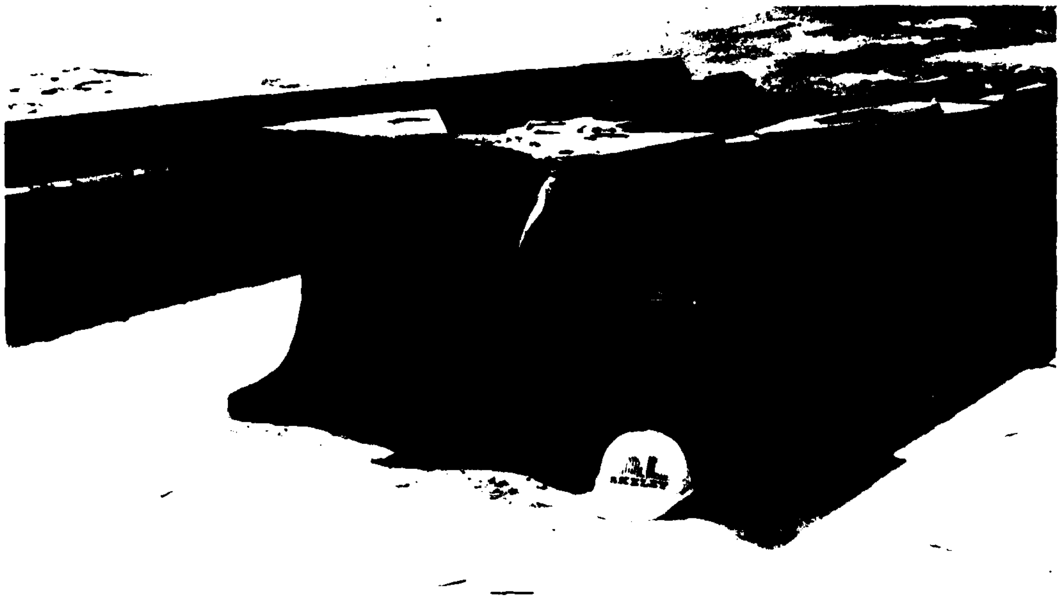
b. Breather tube extends short distance above top of hopper.

Figure 8. Tremie hopper breather pipe

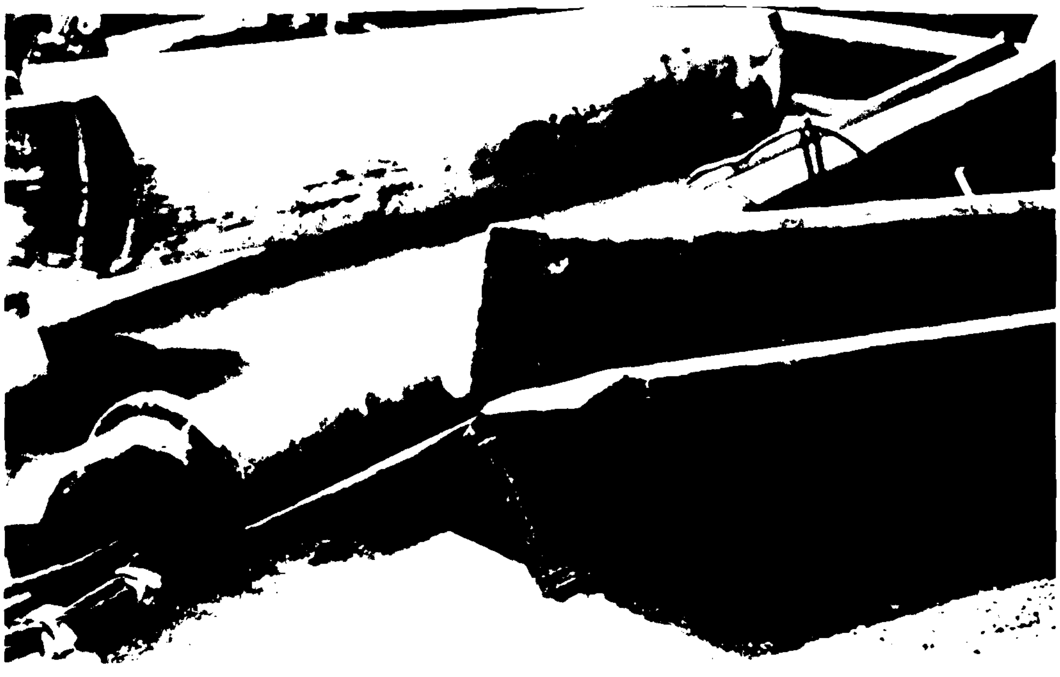
a. Tremie pipe supported by coupling. Loop is used to raise tremie as sections are removed

b. Tremie pipe being raised (note how support plates open to allow passage of couplings)

Figure 9. Tremie support scheme



a. Clam type excavator. The two curved sections ride down adjacent primary elements



b. A variety of drills were used to excavate through rock

Figure 10. Secondary element excavation equipment

PART II: DISCUSSION AND ANALYSIS

19. Of all of the construction steps and procedures involved in the work at Wolf Creek Dam, the only area in which continuing problems were seen was the actual filling of the primary elements of the embankment wall with tremie concrete. The remainder of this report deals with the quality of the concrete placed by tremie and with an examination of the placement procedure to include the concrete mixture.

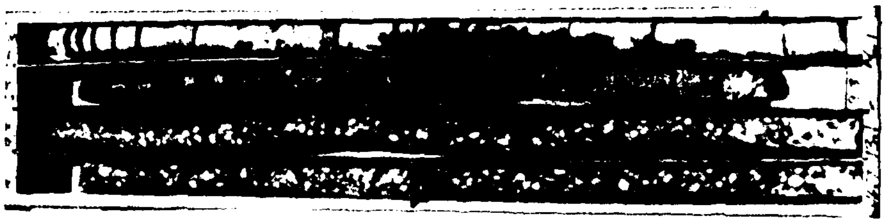
Quality of Tremie Concrete

20. One item in the construction procedure which has not been mentioned previously is the extensive drilling of cores which was done--approximately ten percent of the elements were cored. This coring program revealed minor but persistent problems in the quality of the concrete in the primary elements. These problems included areas of segregated sand or coarse aggregate, voids, zones of trapped laitance, and zones of lightly to extremely honeycombed concrete. Table 1 presents a summary of a core log for one typical primary element, while Figure 11 shows portions of the cores described in the table. Summaries of additional core logs are presented in Appendix A.

21. Review of the information in Table 1 and in other core logs has shown that the areas of poor quality concrete are scattered vertically in the cores and do not appear to follow a discernible pattern. A further analysis of the vertical distribution of the problem areas is given in paragraph 50.

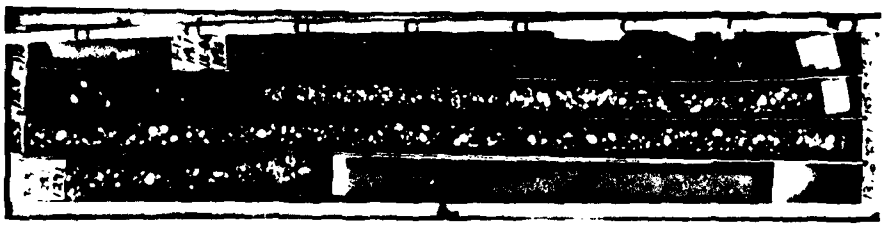
22. Multiple borings taken in the same 26-in.-diam element have shown that the zones of poor quality concrete vary horizontally as well as vertically. For example, in element P465 the first boring showed a 41.5-ft loss of core. A second boring was made which showed good concrete for its full depth. This element is shown schematically in Figure 12.

23. It must be noted that these tremie concrete problems have been found in the primary elements only. Those anomalies which have



a. Elevation 2.3 to 16.7

b. Elevation 103.6 to 118.5



c. Elevation 118.5 to 132.6

Figure 11. Cores from element P773B

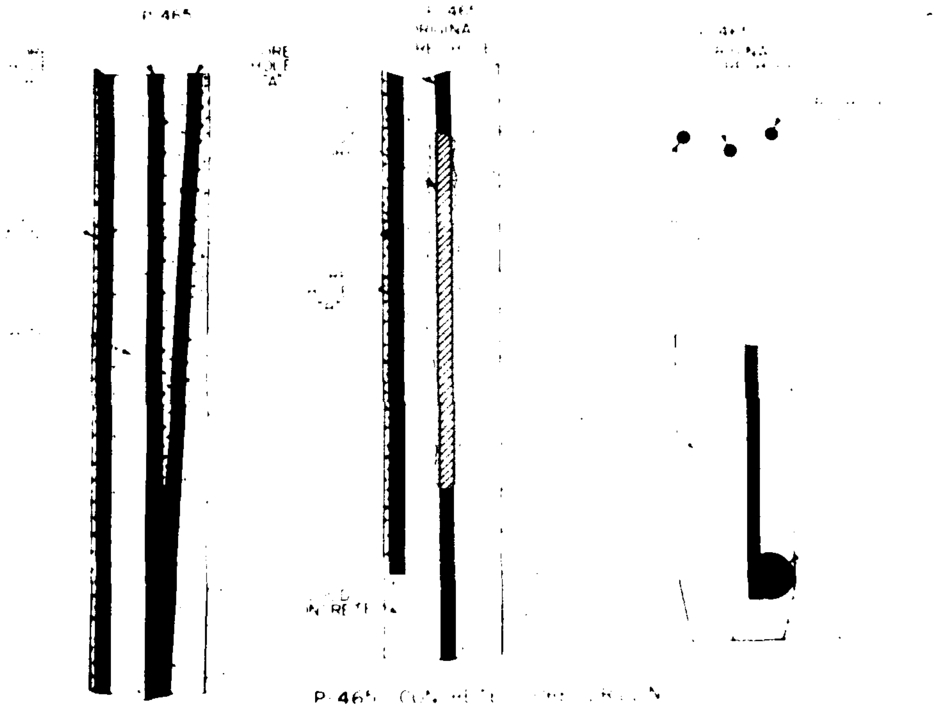


Figure 12. Cores obtained in element P465 showing horizontal and vertical variations in concrete quality

shown up in the cores of the secondary elements have been explained by such factors as loss of drill verticality causing cores to cut into the annular grout near the primary elements or by drilling into a stepped portion of the foundation rock causing loss of a portion of the core. Professional staff at the site were satisfied that all anomalies which have appeared in the cores of the secondary elements could be explained. However, as will be shown below, explanations for the problems discovered in the primary elements are not as readily available.

Analysis of Tremie Procedure

Tremie starting procedure

24. One of the areas suspected of contributing to the concrete problems was the procedure used initially to seal the tremie pipe. The placements were begun with the tremie pipe full of water, and a rubber basketball was used as a "go-devil" to start the concrete flow. The ball, initially floating inside the tremie, was forced down the pipe as concrete was introduced into the hopper. The ball separated the water and the fresh concrete and pushed the water ahead of itself out of the mouth of the tremie. This procedure was abandoned due to the realization that the hydrostatic head in the deep holes collapsed the ball causing a loss of seal in the tremie and a subsequent segregation and washing of the concrete.

25. The technique selected to replace the basketball was to use a pine sphere produced at the site. While this approach does resolve the question of ball collapse, the wooden balls did not fit snugly inside the tremie pipes (neither did the basketball) (Figure 13). There was approximately 0.25-in. clearance between the pine sphere and the tremie pipe. Therefore, as the ball and concrete moved vertically down the pipe, there was some amount of washing of the concrete taking place.

26. To evaluate the importance of the water leakage around the spheres, a cylindrical "pig" was used to start the placement in one primary element. This device was equipped with flexible wipers to provide a very tight seal against the inside of the tremie pipe. Subsequent

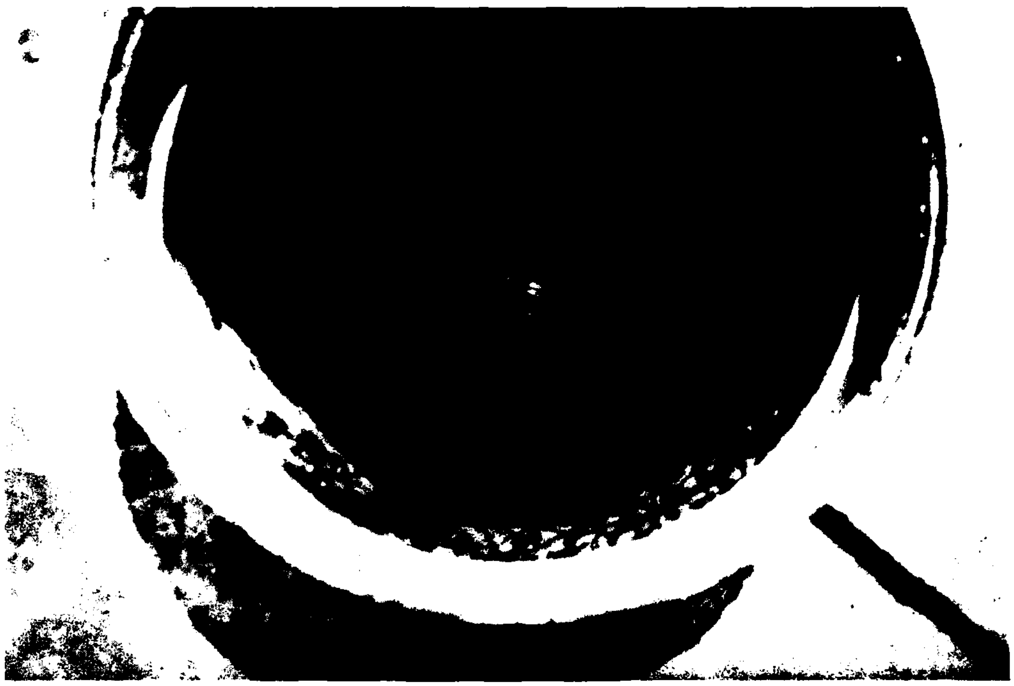


Figure 13. Wooden ball inside tremie pipe at beginning of placement. Note leaks around ball

coring showed that this modification to the procedure did not resolve the concrete quality problem.

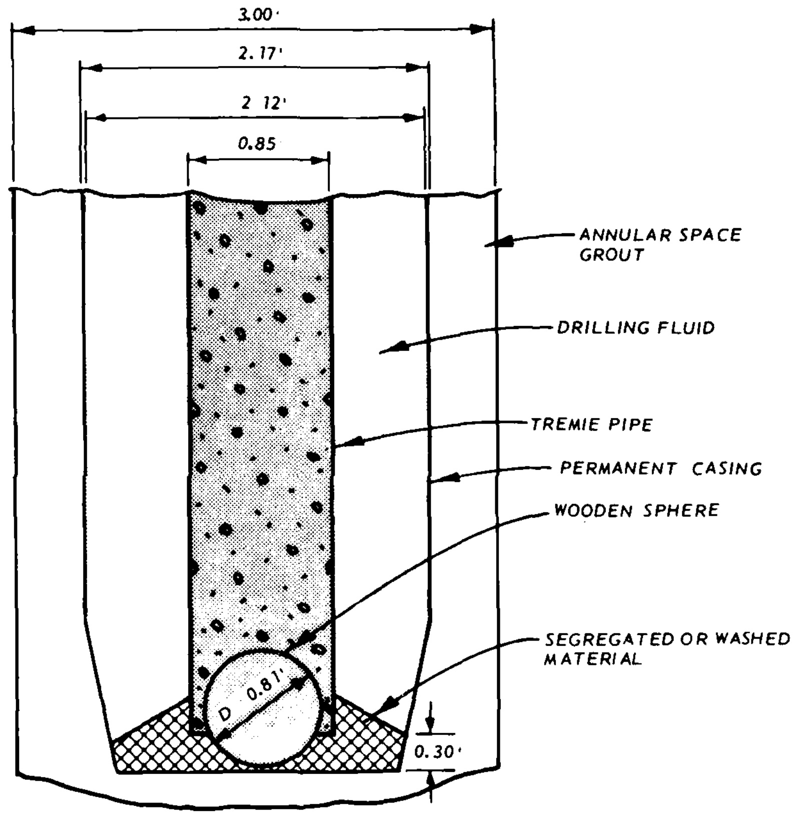
27. The procedure followed to begin concrete placement was also designed to guard against loss of seal. The pipe was initially raised only 0.3 ft as the first concrete was placed. After about 40 seconds of placement (approximately 1 cu yd), the tremie was raised an additional 0.6 ft to allow the pine sphere to escape. By the time the tremie was raised this second increment, sufficient concrete had been fed into the tremie to ensure that the mouth was adequately embedded. This starting procedure is shown in Figure 14.

28. Although there was undoubtedly leakage around the sphere, a zone of laitance or washed material was not consistently found at or near the bottom of the various elements as would be expected. Perhaps the laitance or washed material was carried upward on the sound concrete or perhaps it was lost as an identifiable area due to remixing. However, there is no reason to believe that the zones of poor quality concrete found throughout the vertical sections were a result of initial leakage around the sphere. Finally, the question remains, if the leakage were responsible for the poor quality concrete, why was the problem evident only in the primary elements?

29. One possible explanation relates not to the leakage but to the sphere itself. Due to the size of the primary elements, it was not possible for the sphere to pass the tremie on the way back up the casing, particularly after the centering fins were added (Figure 15). (See discussion of tremie centering below.) Perhaps in some instances the sphere was following the tremie as it was withdrawn and was inhibiting concrete flow. Since the secondary elements were larger, the spheres were more likely to return to the surface without causing this problem.

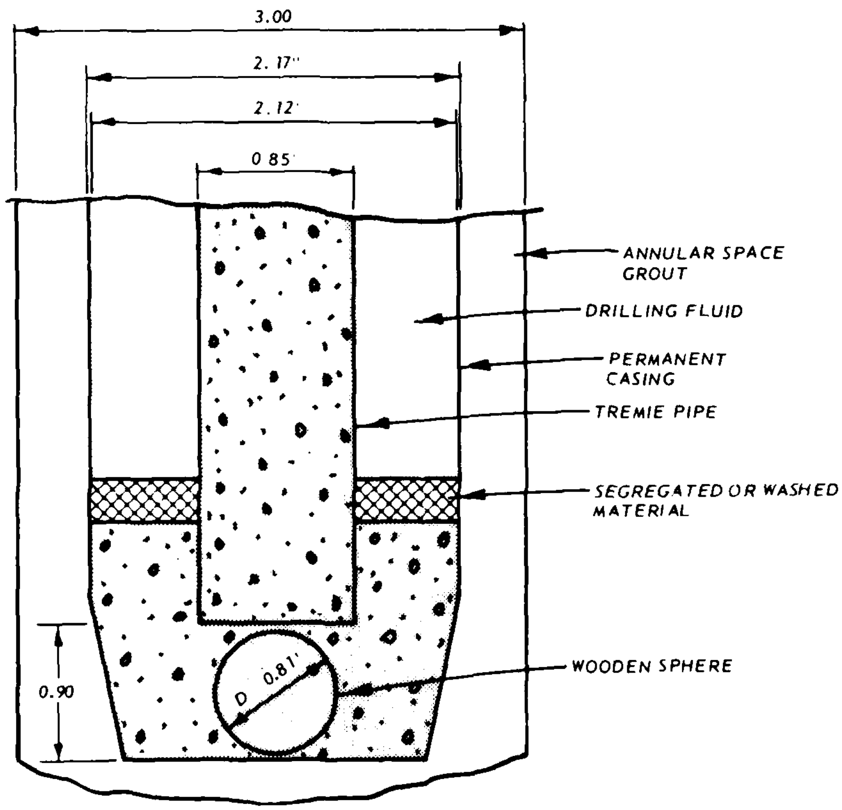
<u>Tremie joint leakage</u>

30. One factor which is often suspected in cases of vertically scattered poor concrete is leakage between joints in the tremie pipe. The rapid downward flow of concrete in the tremie can suck water through any leaks which may be present at the joints. The result is a randomly washed and segregated concrete.



a. Wooden ball in tremie before tremie is lifted initially

Figure 14. Tremie starting procedure (Continued)



b. After tremie is lifted initial increment

Figure 14. (Concluded)

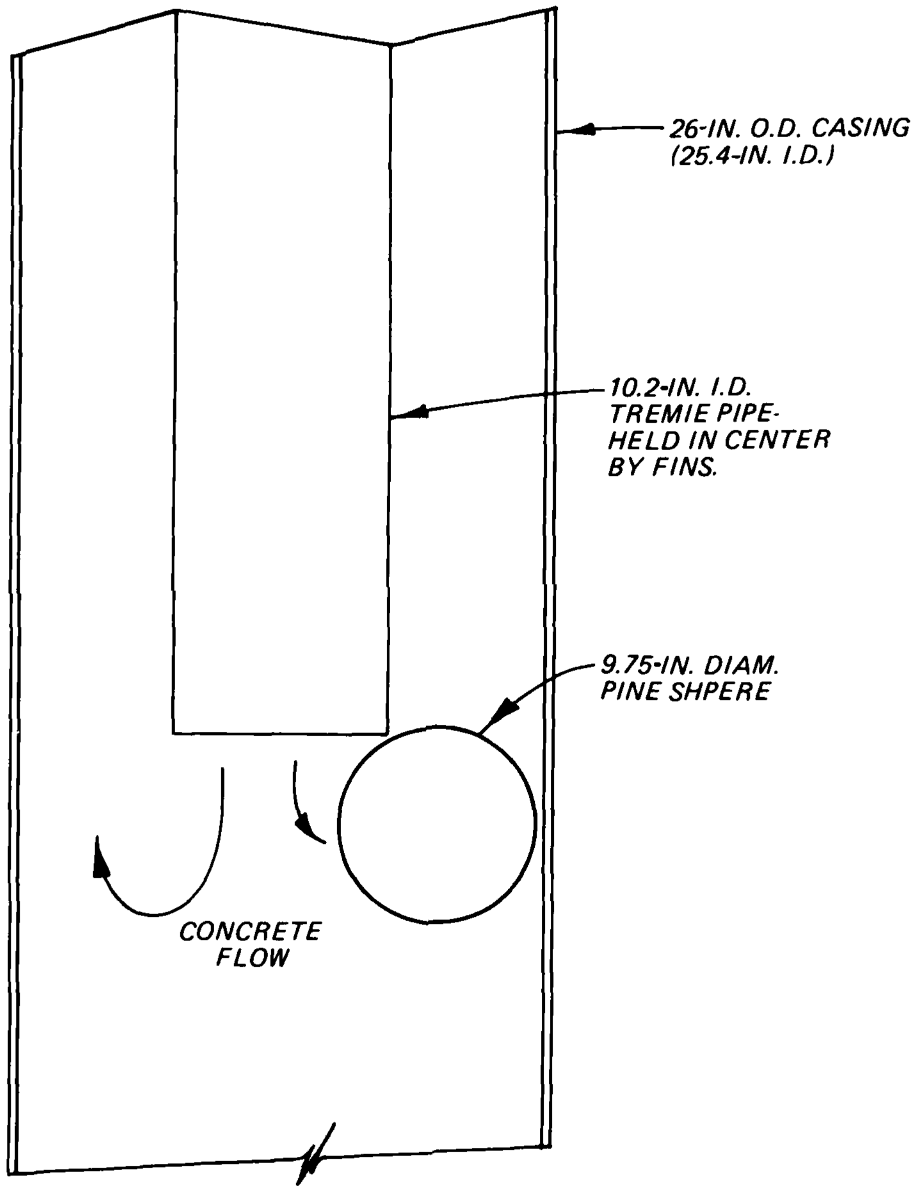


Figure 15. Position of pine sphere upon leaving tremie. Note possible inhibition of concrete flow

31. At Wolf Creek the tremie sections were threaded together and the threads were liberally covered with grease each time the tremie was assembled. The sections were torqued together by two men while a third hit the pipe with a sledge hammer to tighten the connection. All sections of tremie pipe were numbered to ensure that they were assembled in the same sequence for all placements.

32. The tremie was also tested for leakage by lowering a light inside and found to be satisfactory. From the precautions which were taken, it is doubtful that tremie leakage was causing the problems.

Tremie centering

33. Another potential problem area was the centering of the tremie in the holes--particularly the primary elements. If the pipe were not centered, there was a possibility of inhibiting the flow of the concrete as it left the tremie mouth. To eliminate this possibility, centering fins were added to the section of the tremie pipe above the mouth (Figure 16). While this modification did ensure proper centering of the tremie pipe, it raised the question of inhibiting the return of the wooden sphere described above. Cores taken after addition of the fins continued to show anomalies, indicating that the fins had not resolved the overall problem.

Concrete placement rate

34. In large volume placements the placement rate of tremie concrete is often an area of concern. Too slow a placement rate allows the concrete in place to stiffen which inhibits flow. Table 2 presents placement rates for several elements at Wolf Creek. These rates are based upon total elapsed time from beginning to end of the placement and, therefore, include time for removal of pipe sections, waiting on concrete trucks, etc.

35. The lower volumetric rate (cubic yards/hour) for the primary elements is a reflection of the more frequent stopping for removal of pipe sections. Yet even with this slower volumetric rate, the primary elements have a higher linear rate (feet/hour) due to their smaller cross-sectional area. The linear rate appears to be significantly higher for the primary elements.

Figure 16. Fins added to tremie pipe
to ensure proper centering

36. Although problems with rate are usually associated with too slow a placement, perhaps too rapid a rate may also be detrimental. No reports on the effects of too rapid a placement have been found in the literature. Intuitively, however, a higher rate would seem to favor remixing within the elements as the concrete is placed.

Tremie removal rate

37. An aspect closely related to the placement rate is the rate at which the tremie pipe is pulled from the hole as sections are removed. Here, the theory is that too rapid a pull rate could result in voids or honeycomb if the concrete did not flow fully into the void left by the tremie pipe. This problem is particularly prevalent if overall placement rates are low.

38. To guard against too rapid removal of pipe from the elements at Wolf Creek, an inspector timed and recorded the pull rate for each section of the tremie. The same rate (0.3 ft/sec) was used for both the primary and secondary elements.

39. Again, the question may be raised as to why the problem concrete, if a result of pipe pull speed, is evident in only the primary elements. This question is particularly bothersome since the tremie sections were removed more frequently from the primary elements. Hence, the concrete had less time to stiffen and lose the ability to flow into the void possibly created by the withdrawing tremie. Therefore, if pipe removal rate were a factor, the problem would seem to have been less likely to occur in the primary elements.

Breaks in placing

40. Another area of concern was the resumption of concrete placing at the beginning of each new truckload. A certain amount of sand and laitance does collect on the top of the tremie concrete as the placement moves up the hole. To prevent trapping this material at the resumption of placement, the initial amount of concrete was trickled into the tremie. The remainder of the load was unloaded at normal speed. This same procedure was followed when a truckload was broken into two placements to allow removal of a tremie section. As will be discussed below, there does not appear to be a correlation between

stopping/restarting points and zones of poor quality concrete.

Water temperature during placement

41. In the original construction sequence there was not a delay between placement of the grout in the annular space surrounding the primary elements and placement of the tremie concrete in the elements. The temperature of the water in one element was measured at 100°F due to the heat generated by the hydration of cement in the annular grout. Placement of tremie concrete into hot water can result in rapid and unpredictable setting or loss of slump, which could inhibit the flowability. In one instance, a rapid set required removal of a portion of the concrete in an element.

42. These problems led to the practice of allowing 10 days between placement of annular grout and tremie concrete. The water in the primary elements was also exchanged for cooler water prior to concrete placement. While this change in procedure did eliminate rapid set problems and probably helped improve concrete quality, it did not completely eliminate the concrete quality problems as described.

Concrete mixture

43. One area in which a change was made during the project which resulted in a noticeable improvement was the tremie concrete mixture itself. The final mixture is shown in Table 3. Of interest in this mixture is the use of a fly ash which was included in the original mixture to improve workability and to reduce heat generation. None of the problems observed were directly attributable to the mixture. However, the slump loss characteristics of such a rich mixture and the high ambient temperature at the site suggested that the addition of a retarder to the concrete would be beneficial. A retarder was added and subsequent placements appeared to be very successful. The Resident Engineer felt that the retarder made a significant difference, particularly by decreasing the amount of laitance and by improving the appearance of the concrete as it returned to the top of the holes at the conclusion of a placement.

Improvements in concrete quality

44. Table 4 presents coring data that show that a definite

improvement in concrete quality was seen during the project. While these data are presented in terms of before and after the addition of the retarder to the concrete mixture, the following items must be noted:

- _a_. The addition of the centering fins to the tremie pipe and the addition of the retarder to the concrete mixture were done at approximately the same time during the second phase of the project.
- _b_. The switch to the wooden sphere to start the placements and the steps taken to reduce the water temperature during placement occurred during the first phase of the project.

Therefore, it is impossible to state that any one measure was solely responsible for the improvements in concrete quality which were seen.

Observations of placements

45. Shortly after the addition of the retarder to the mix, the authors of this report made a joint observation of the placement of several primary elements and one secondary element. During the placements which were observed (and during subsequent placements) the concrete returning to the surface appeared to be of the same quality as that which was being supplied to the tremie (Figure 17).

46. Another area which had been questioned was how to determine when sound concrete had reached the top of the elements. For the primary elements there was no difficulty making this determination. Initially, clear water overflowed the casing. Near the end of the placement, the small amount of slurry which was added to the primary elements began to appear. This slurry gradually thickened and contained more and more granular material. Approximately 12 to 18 in. of very granular material came to the surface before a concrete containing fine and coarse aggregate was visible. This concrete appeared evenly on all sides of the tremie and had a very uniform appearance. (Before the retarder and fins were added, elevation differentials of up to 18 in. on opposite sides of the tremie were reported as the concrete began to return.)

47. The observations of the concrete placement in the secondary element were identical to those in the primary elements except that all

Figure 17. Primary element at completion of placement. Concrete appeared to be of excellent quality

fluid which was displaced was slurry rather than water. The same thickening of the slurry was noted and, again, there was no difficulty determining when sound concrete had returned.

Core and placement logs

48. The results obtained from coring elements placed after the addition of the retarder to the concrete mixture were suprising and disappointing. Although the secondary elements continued to be free of problems, the zones of poor quality concrete continued to be found in the primary elements. While the problems did not appear to be as severe as before the addition of the retarder, they were still evident.

49. A very detailed system of recording the work on the wall was established by the Resident Engineer. There were data sheets for each aspect of the work--excavation, casing placement and alignment, tremie concreting, and coring. These reports were filed on a day by day and element by element basis. Samples of tremie placement data sheets and data concerning tremie pipe embedment during the placement of 14 elements as extracted from the project records are presented in Appendix B. A summary of this placement data is given in Table 5. As can be seen in this table, there is very little difference between the primary and secondary elements for tremie pipe embedment at the beginning of a lift of concrete. There is a greater difference shown for the tremie embedment at the end of each lift--the concrete was placed approximately 8.3 ft higher in each lift in the primary elements before the tremie pipe was raised. Whether this difference had a direct influence on the concrete problems as described is unknown.

50. Table 1, presented earlier, summarized the core log of one element. Additional core log summaries are presented in Appendix A. Using both the placement summary information and the corresponding core logs, Figures 18 through 23 were prepared in an attempt to correlate zones of poor quality concrete with any of the following factors:

a. Pipe embedment at beginning or end of a batch of concrete;

b. Breaks in placement to withdraw tremie sections; and

c. Elevations of the end of the tremie.

Study of these figures does not reveal any factor which is clearly

1. EACH FIGURE (19 THROUGH 23) PRESENTS AN ANALYSIS OF THE TREMIE PIPE LOCATION ON THE LEFT OF THE PAGE AND A SUMMARY OF THE CORE LOG ON THE RIGHT OF THE PAGE.
2. EACH VERTICAL LINE REPRESENTS PLACEMENT OF CONCRETE FROM THE BOTTOM TO THE TOP OF THE LINE. THE TREMIE IS FIXED DURING EACH PLACEMENT WITH THE MOUTH AT THE BOTTOM OF THE LINE.
3. EXAMPLE

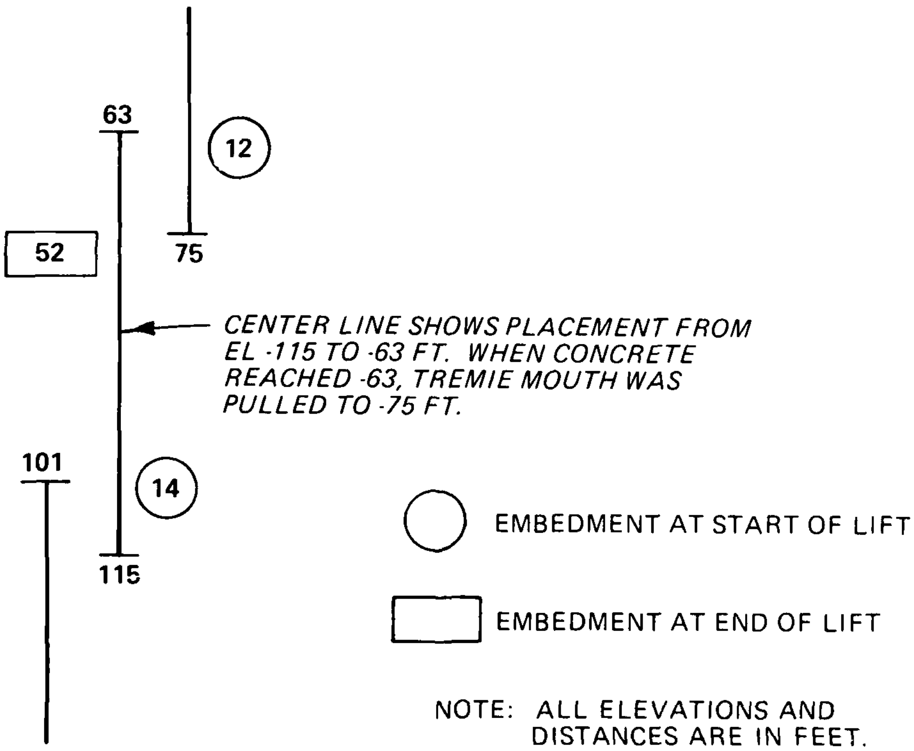


Figure 18. Key for Figures 19 through 23.

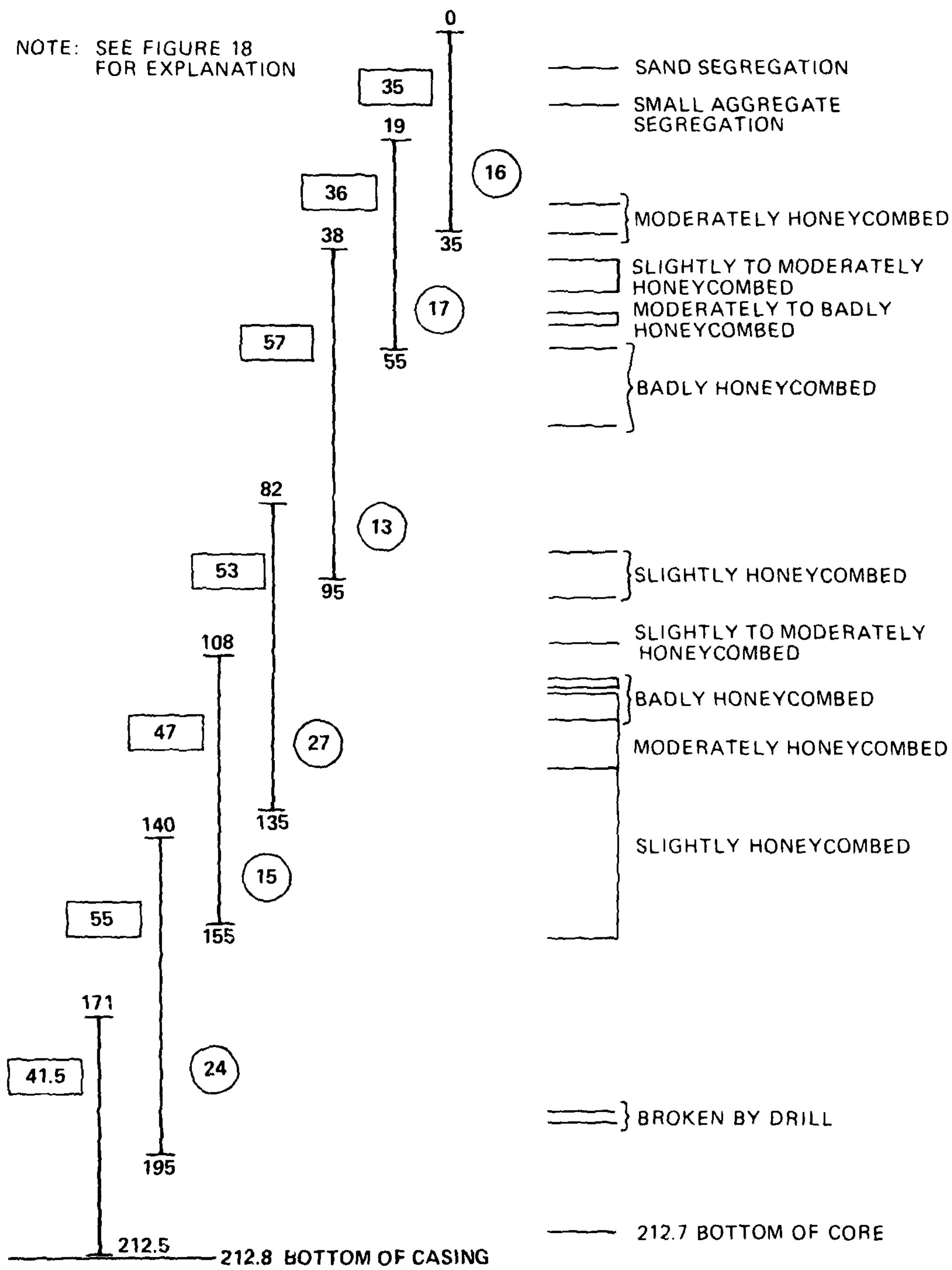


Figure 19. Analysis of element P611

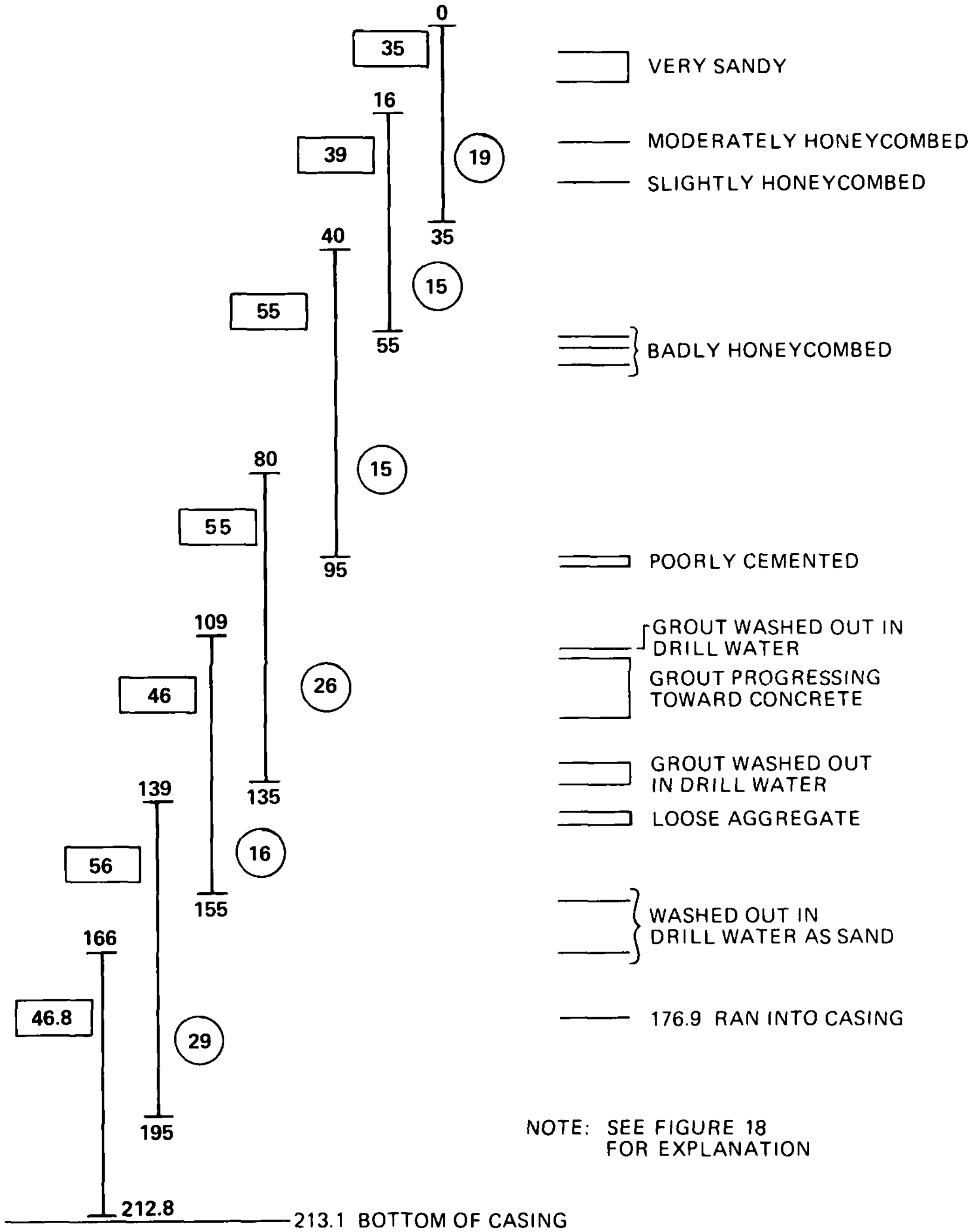


Figure 20. Analysis of element P773

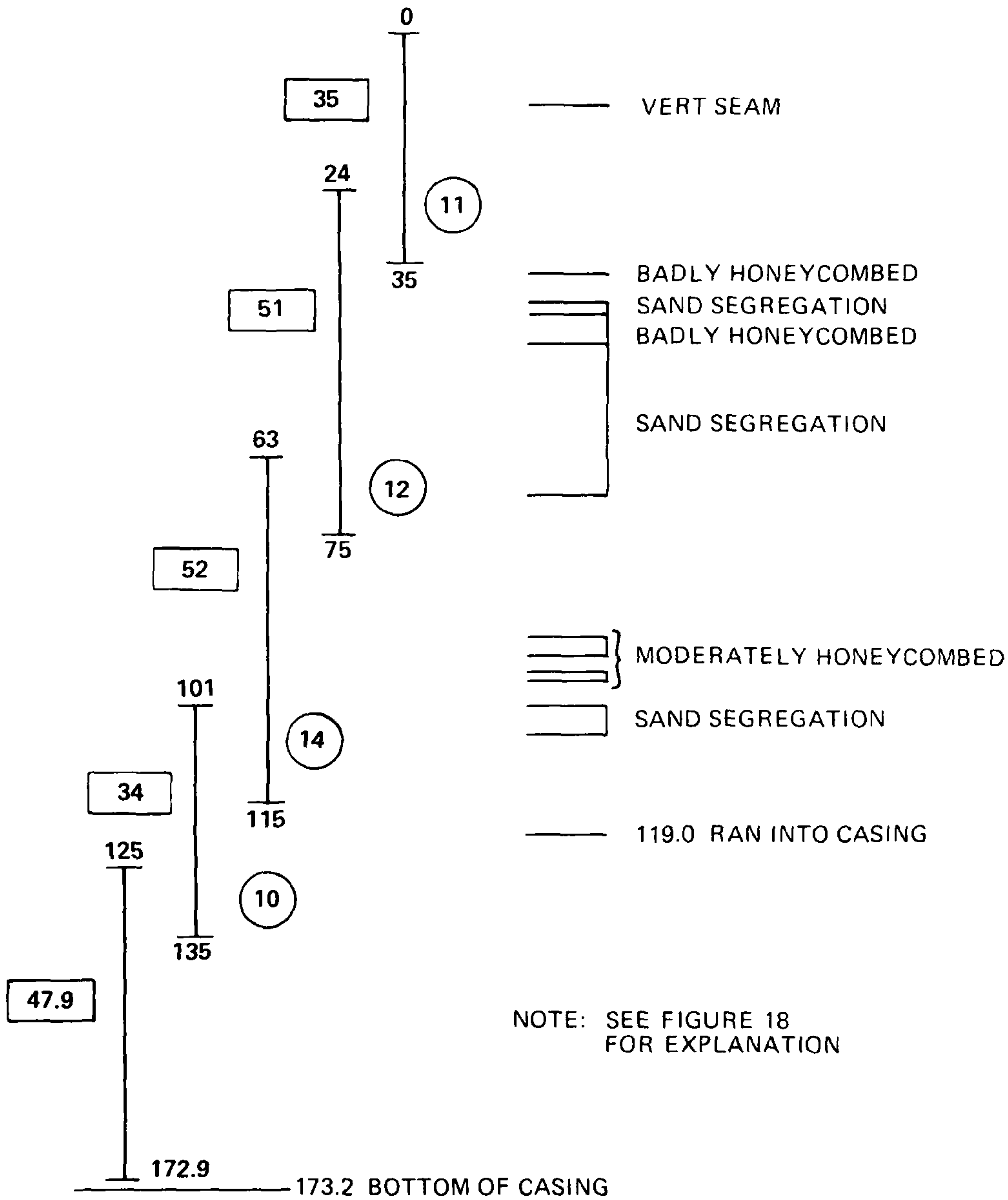


Figure 21. Analysis of element P985

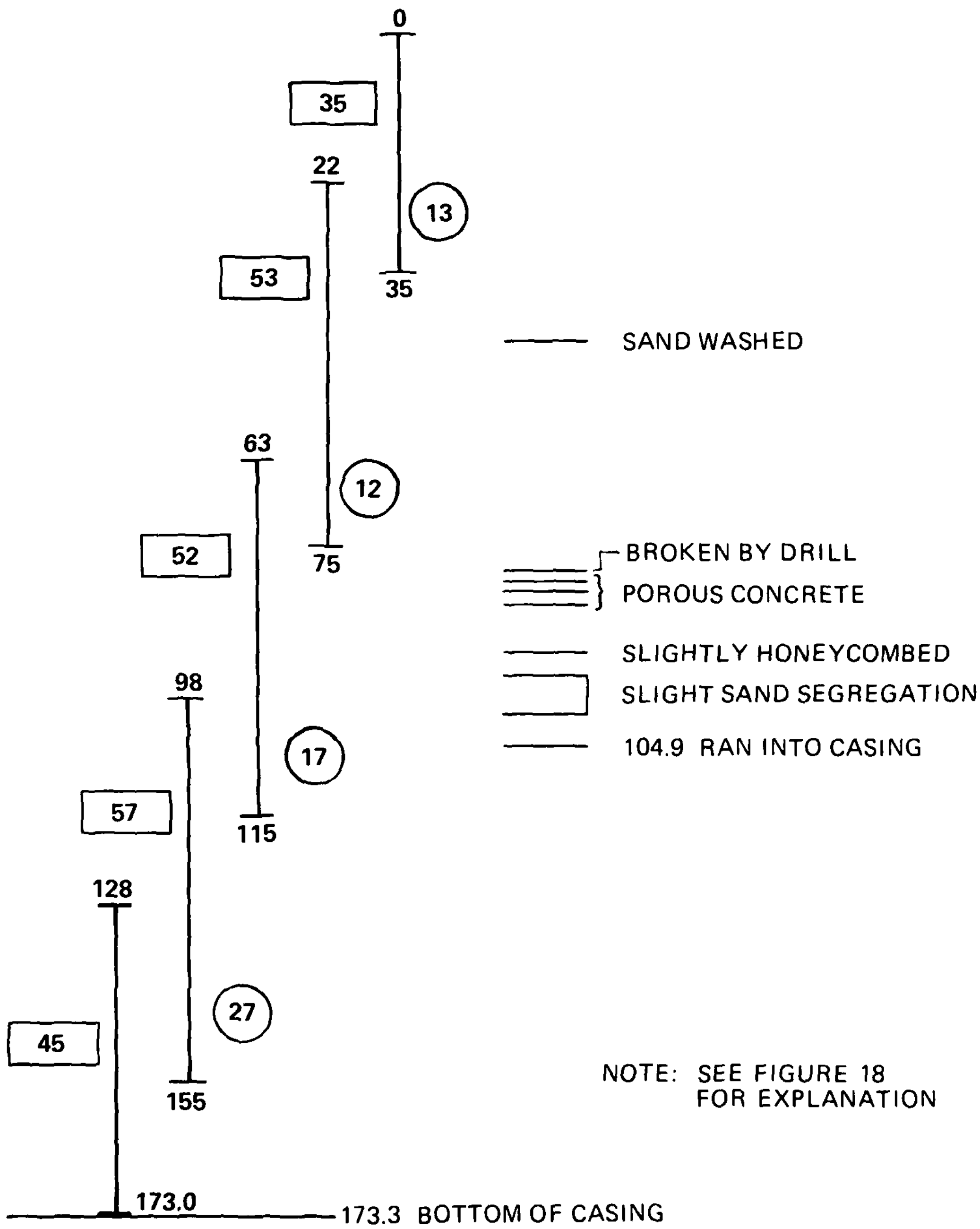


Figure 22. Analysis of element P1001

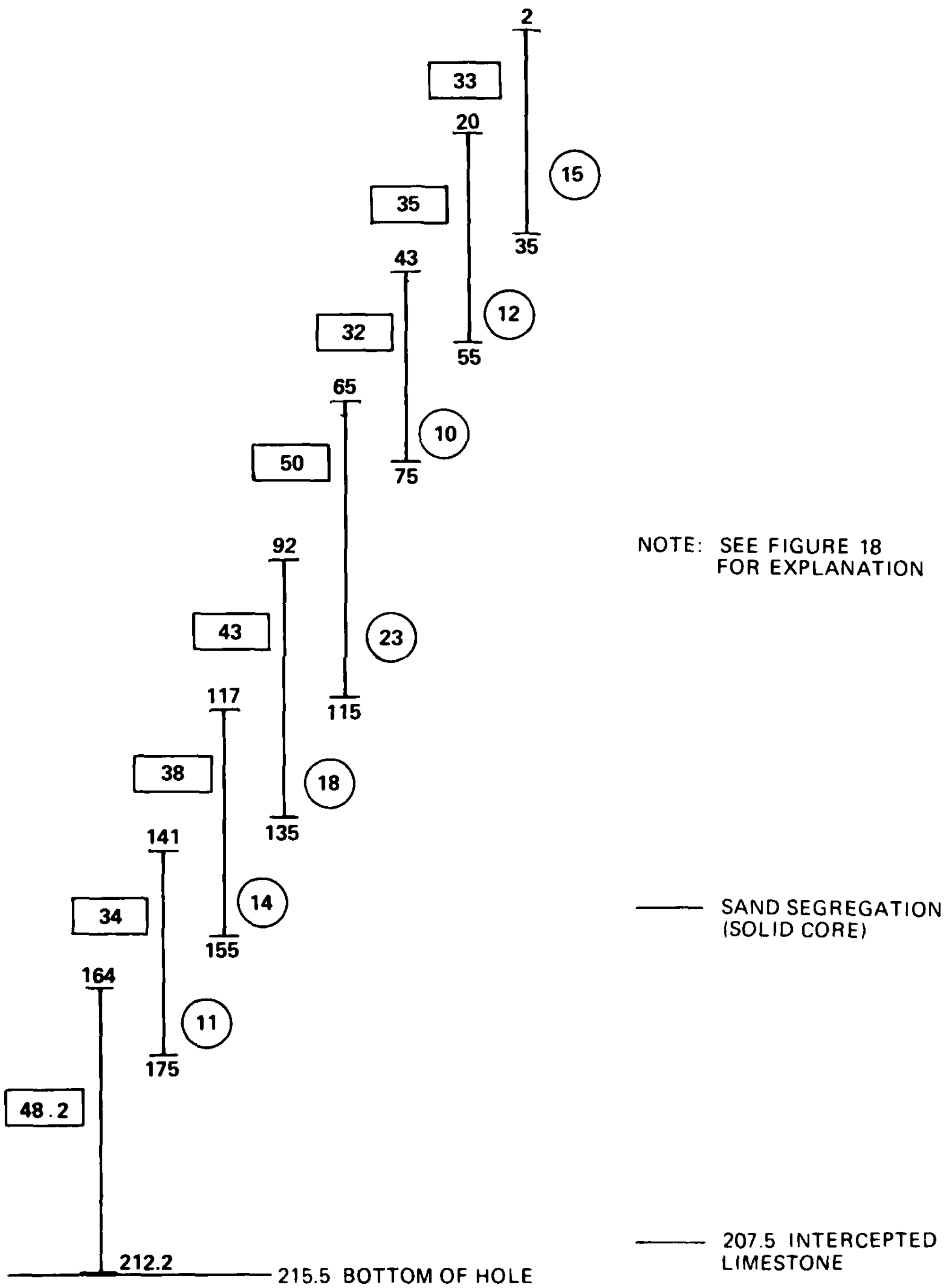


Figure 23. Analysis of element S576

related to the zones of poor quality concrete.

Tremie resistance to flow

51. Another area which was considered was the balance of the tremie system when flow was not occurring due to breaks in the placement. This balance may be thought of in terms of resistance to flow, which may be calculated as the difference between the theoretical hydrostatic balance of the tremie system and the actual measured value. The difference which is obtained may be attributed to friction between the concrete and the tremie pipe, to internal friction or cohesion of the concrete, or to a blockage or any other type of restriction to flow. Figure 24 shows the geometry of the tremie system and the technique used to calculate this resistance to flow.

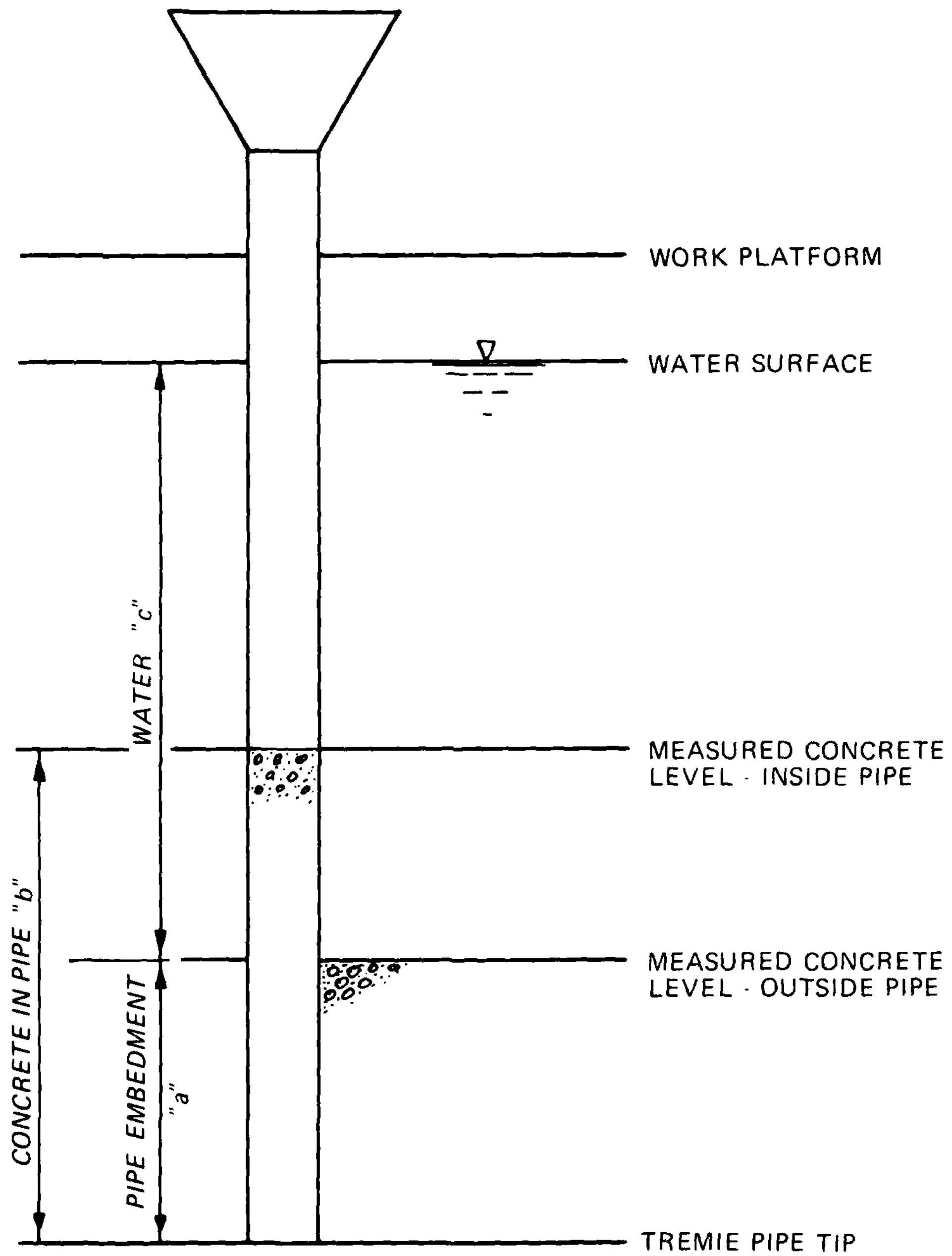
52. Measurements made on various placements have shown that the tremie system is typically very close to the balance point and very little resistance to flow can be measured. Measurements were made for six elements at Wolf Creek, and a summary of the data is in Table 6. (Complete data for these measurements are presented in Appendix C.)

53. The data in Table 6 show that the resistance to flow varies greatly from measurement to measurement, and a certain degree of this variation is to be expected. Not enough work has been done in this area to determine what a typical range of values would be. However, note that given very close mean values, the standard deviation for the primary elements is almost double that for the secondary elements. Note also the extreme values which appear in two of the three primary elements. Unfortunately, none of the elements for which this resistance to flow data were taken were cored.

54. While these variations in resistance to flow are not believed to be causing the problems seen in the concrete, they may be indicative of blockage or other restrictions to concrete flow which could result in the anomalies detected. If these variations are related to zones of poor quality concrete, measurements inside and outside the tremie pipe during placement could serve as an additional inspection tool.

Potential for concrete segregation

55. The data concerning resistance to flow also point out the



NOTE: AT PIPE TIP: $b\gamma_{conc} = c\gamma_{water} + a\gamma_{conc}$ + (RESISTANCE TO FLOW)

RESISTANCE TO FLOW = $(b-a)\,\gamma_{conc} - c\gamma_{water}$.

Figure 24. Tremie geometry and derivation of resistance to flow

high potential for concrete segregation which occurred whenever there was a break in placement. Since the tremie system returned to essentially the balanced condition, concrete placed immediately after a break was subjected to a long, free fall which could have resulted in significant segregation.

56. Tremie concrete placements are often thought of in terms of concrete flowing gently down the pipe after being introduced into the hopper. The Civil Works guide specification (U. S. Army Corps of Engineers, 1978) states that the tremie should be "kept full of concrete to a point well above the water surface." This approach is predicated upon being able to control the exit of concrete from the tremie by raising or lowering the pipe.

57. The Civil Works guide specification and the general notions of controlling tremie concrete flow are based upon experience gained during mass placements in which such control may be attainable. However, for small-volume, confined placements such as those at Wolf Creek, the concrete in place does not become sufficiently stiff to allow for control of flow based upon pipe embedment. (Such control might be attainable if extremely deep embedments were maintained.) This lack of control implies that large amounts of concrete may have been falling rather than flowing down the tremie pipe throughout the placements rather than just after breaks in placement. This thought is supported by observations of the placements.

58. Based upon these considerations, it is highly probable that segregation was occurring--particularly after breaks in placement and, possibly to a lesser degree, during the entire placement process. There is no reason to believe that there were differences in segregation potential between the primary and secondary elements at Wolf Creek.

PART III: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

59. Use of tremie-placed concrete to construct a positive cutoff wall at Wolf Creek Dam has been a highly successful operation which will help to ensure the continued safety of the structure. (Fetzer 1979a and 1979b). The overall quality of the concrete placed by tremie has been excellent, with the exception of scattered nonhomogeneous areas which have been found by coring. These problem areas have been limited to the primary elements and include zones of trapped laitance, voids, segregated aggregates, and honeycomb ranging from slight to severe. Since the problems have been limited to the cased primary elements, there is no reason to believe that the wall will not serve its intended purpose.

60. This analysis of the Wolf Creek tremie concrete operation has revealed no single item in the construction process which could be modified and which would thus eliminate the concrete problems encountered. Instead, the problems are believed to be the result of several interrelated items which produce a phenomenon which has not been previously reported for tremie placements.

61. Control of tremie concrete flow through pipe embedment length as is advocated for mass placements is apparently not applicable to deep, small-volume, confined placements such as those at Wolf Creek. Therefore, concrete was probably falling through distances large enough to result in significant segregation.

62. To offset this segregation, remixing was apparently taking place within the elements as the concrete flowed out of the tremie. This remixing seems to have been more successful in the secondary elements than in the primary elements. There were apparently three factors which may have contributed to an inhibition of remixing in the primary elements. These were:

a. The primary elements have a much smaller cross-sectional area than the secondary elements. This smaller area may

have been acting in conjunction with the wooden sphere and tremie pipe creating a condition which restricted flow and remixing.

b. The walls of the permanent casings which were filled to create the primary elements were much smoother than the walls of the secondary elements. The smoother walls may have reduced the tendency for the concrete to tumble and remix. Additionally, the introduction of the small amount of bentonite slurry into the primary elements prior to starting concrete placement may have increased the smoothness of the casing walls.

c. The concrete was placed in the primary elements very rapidly. The rate may have been too rapid to allow for normal flow and adequate remixing to take place.

63. A fourth factor may also be identified--the embedment length of the tremie pipe at the end of a lift of concrete. While the data presented (see Table 5) showed a greater embedment depth for the primary elements, it is not known whether this factor had an effect on the concrete quality.

64. A definite reduction in concrete problems was seen over the duration of the project. This reduction may be attributed to a series of modifications in the placement technique and to the addition of a retarder to the concrete mixture. All of the modifications enhanced the flowability of the concrete and therefore contributed to better remixing in the primary elements. Since the effects of these modifications were cumulative, it is impossible to state which made the greatest difference. The Resident Engineer strongly believes that the addition of the retarder to the concrete mixture was the most significant change.

Recommendations

65. The use of tremie-placed concrete for rehabilitation projects of this nature has been successfully demonstrated at Wolf Creek. However, in future similar projects which involve tremie-placed elements of small cross-sectional area, engineering and construction personnel must be made aware of the potential for problems which exists.

66. Construction of tremie-placed cutoff walls using small diameter uncased elements does not appear to ensure a complete cutoff.

Recommendations for such construction should be carefully reviewed in light of the information presented in this report.

67. For future similar placements, the use of a concrete mixture with a high degree of flowability and the minimizing of all restrictions to flow will give the greatest probability of a successful placement. The unique problems inherent at each placement may require studies or research to ensure development of an adequate concrete mixture.

68. Additional work is required to develop techniques for deep tremie placements which will reduce the potential for segregation noted herein.

69. Additional work is also required concerning the significance of the variations of the flow resistance measurements as identified in this report. This work could best be carried out at an actual placement rather than in a laboratory environment.

70. The current Civil Works guide specifications covering tremie placement are based upon experience gained from placements in larger areas and do not consider the problems and difficulties involved in placements of the nature of those at Wolf Creek. While the project specifications for Wolf Creek (Appendix D) are more detailed than the guide specifications, they were prepared prior to the work represented by this report. Specifications for future projects must include consideration of the problems identified in this report. Based upon additional field experience and research, and if justified by project demand, future editions of the appropriate Civil Works guide specifications and the Standard Practice for Concrete should include sections dealing with tremie placements of the type described in this report.

71. The problems identified in this report have bearing not only on the construction of diaphragm walls but also on all deep, confined tremie concrete placements such as cast-in-place piles or piers or the filling of precast concrete elements.

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Table 1

Summary of Core Log, Element P773 (Primary Element)*

Depth, ft From	Depth, ft To	Concrete Description
--	2.3	Top of concrete
2.3	3.9	Grout
3.9	9.3	Less than 25 percent normal aggregate (very sandy)
9.3	20.2	Concrete with 3/4-in. maximum well rounded quartz aggregate (sound concrete)
20.2	21.5	Moderately to slightly honeycombed
21.5	27.4	Sound concrete
27.4	28.9	Slightly honeycombed
28.9	54.0	Sound concrete
54.0	54.4	Severely honeycombed
54.4	54.9	Sound concrete
54.9	55.1	Severely honeycombed
55.1	55.8	Sound concrete
55.8	56.2	Severely honeycombed
56.2	59.0	Sound concrete
59.0	59.3	Moderately honeycombed
59.3	60.2	Sound concrete
60.2	60.1	Severely honeycombed
60.1	94.8	Sound concrete
94.8	96.6	Poorly cemented, seemed to be an overabundance of aggregate
96.6	114.9	Sound concrete
114.9	115.7	Not recovered - grout washed out in drill water
115.7	116.7	Grout with little or no sand
116.7	119.1	Slightly sandy grout getting progressively sandier
119.1	122.8	Less than 25 percent normal aggregate
122.8	130.0	Sound concrete
130.0	130.6	Loose aggregate - coated with cemented material
130.6	133.1	Not recovered - washed out in drill water as sand

(Continued)

* Tables of additional core log summaries may be found in Appendix A.

Table 1 (Concluded)

Depth, ft		Concrete Description
From	To	
133.1	138.3	Sound concrete
138.3	141.0	Loose aggregate with cement adhering to surface (indicates concrete was solid before drilling)
141.0	142.6	Slightly honeycombed
142.6	151.0	Sound concrete
151.0	151.3	Broken by drill
151.3	156.7	Sound concrete
156.7	157.5	Not recovered - washed out in drill water as sand after being broken up by drill
157.5	158.0	Sound concrete
158.0	159.3	Not recovered - same as 156.7 to 157.5
159.3	175.5	Sound concrete
175.5	176.9	Left in hole
176.9	--	Hit casing

Table 2

Tremie Concrete Placement Rates

Element	Elapsed Time hr	Element Depth ft	Linear Rate ft/hr	Volume of Concrete cu yd	Volumetric Rate cu yd/hr
P611	1.1	212.8	193	30	27
P771	1.2	212.8	177	29.5	25
P773	1.4	213.1	152	29.5	21
P791	1.1	212.9	194	30	27
P795	1.2	212.9	177	30	25
P807	1.2	212.7	177	29.5	25
P985	0.9	173.2	192	25	28
P1001	0.9	173.3	193	25	28
PRIMARY ELEMENT AVERAGE			182	NA	26
S576	1.6	212.5	133	72	45
S594	1.7	212.6	125	72	42
S676	2.1	212.7	101	75	36
S746	1.8	212.9	118	73	41
S858	2.2	263.2	120	97	44
S956	1.5	172.7	115	64	43
SECONDARY ELEMENT AVERAGE			119	NA	42

Table 3

Tremie Concrete Mixture

Wolf Creek Dam (SSD Weights)

Cement	564 lb/cu yd
Fly ash	123 lb/cu yd
Coarse aggregate	1619 lb/cu yd
Fine aggregate	1369 lb/cu yd
Water	275 lb/cu yd
Air entraining admixture	6 to 9 oz/cu yd
Retarder/water reducer	18 oz/cu yd
Slump range	6.5 to 7.5 in.
28-day strengths	
with retarder	4685 psi
without retarder	4770 psi
specified	3000 psi

Fine aggregate, percent of total aggregate = 46

Water-cement plus fly ash ratio = 0.40

Table 4

Improvements in Concrete Quality*

Before retarder and other measures
- 24 primaries cored
- 10 showed core loss

After retarder and other measures
- 5 primaries cored
- None showed core loss

* See paragraph 44 for discussion of sequence of modifications to placement procedure and concrete mixture. No further changes in either were made after addition of the retarder.

Table 5

Tremie Pipe Embedment Summary*

Element	Average Embedment of Tremie: At Beginning of Lift, ft	Average Embedment of Tremie: At End of Lift, ft
P611	16.5	46.4
P771	18.2	45.9
P773	18.3	47.5
P791	20.5	47.7
P795	20.2	47.5
P807	20.7	48.1
P985	14.3	44.0
P1001	17.3	48.4
Averages - Primary Elements	18.3	46.9
S576	14.7	39.2
S594	14.4	38.9
S676	17.4	38.8
S746	19.6	40.8
S858	18.5	37.2
S956	15.5	36.9
Averages - Secondary Elements	16.7	38.6

* Data summarized in this table are presented in detail in Appendix B.

Table 6

Tremie Resistance to Flow Summary*

	Element P791		Element P795		Element P807		Element S746		Element S858		Element S956	
Reading	Total lb/ft^2	Per Ft lb/ft	Total lb/ft^2	Per Ft lb/ft	Total lb/ft^2	Per Ft lb/ft	Total lb/ft^2	Per Ft lb/ft	Total lb/ft^2	Per Ft lb/ft	Total lb/ft^2	Per Ft lb/ft
1	3433	18.8	2785	15.7	1222	7.2	1195	7.0	1313	6.6	866	5.6
2	1017	5.6	1005	5.6	1798	9.7	1776	9.8	-523	-2.9**	1029	8.9
3	710	4.9	519	3.5	499	3.3	1272	9.4	693	4.8	1144	9.9
4	1019	6.6	1447	9.4	989	6.5	1012	7.6	603	4.4	815	7.6
5	677	5.1	798	5.8	798	5.9	1047	8.2	-954	-7.9**	658	7.0
6	1353	15.0	847	10.1	180	2.3**	1059	8.8	577	4.6	613	7.5
7	292	4.3**	146	2.1**			684	5.8	1238	10.1		
8							657	9.7	728	6.7		
9									499	5.4		
10									544	6.5		

AVERAGE: PRIMARY ELEMENTS: 8.2 lb/ft; SECONDARY ELEMENTS: 7.1 lb/ft

STANDARD DEVIATION: PRIMARY ELEMENTS: 4.5 lb/ft; SECONDARY ELEMENTS: 2.3 lb/ft

* Data summarized in this table are presented in detail in Appendix C.

** Values not included in averages.

APPENDIX A: SUMMARIES OF CORE LOGS OF SELECTED ELEMENTS

1. Tables A1 through A4 present summaries of core logs for elements P611, P985, P1001, and S576. The core log for element P773 was presented earlier in the text in Table 1. Of these elements, all except P773 were placed using concrete containing the retarding admixture.

2. Figures 19 through 23, in the text, relate these core logs to the placement logs for the particular elements.

Table A1

Summary of Core Log, Element P611 (Primary Element)

Depth, ft From	Depth, ft To	Concrete Description
--	2.6	Top of concrete
2.6	6.1	Sandy grout with little aggregate
6.1	6.8	Sand segregation, less than 50 percent normal aggregate
6.8	12.8	Concrete with 3/4-in. maximum well rounded quartz aggregate (sound concrete)
12.8	13.9	Segregation of small gravel Z 1/4 in. diameter
13.9	30.5	Sound concrete
30.5	31.0	Moderately honeycombed and broken by drill
31.0	35.1	Sound concrete
35.1	35.5	Moderately honeycombed
35.5	38.1	Sound concrete
38.1	38.5	Moderately honeycombed
38.5	38.8	Sound concrete
38.8	39.1	Broken by drill
39.1	45.1	Slightly to moderately honeycombed
45.1	49.2	Sound concrete
49.2	51.6	Moderately to badly honeycombed
51.6	55.0	Sound concrete
55.0	55.5	Severely honeycombed
55.5	57.0	Sound concrete
57.0	58.8	Moderately honeycombed and broken by drill
58.8	59.6	Severely broken portion washed out as sand in drill water
59.6	67.3	Sound concrete
67.3	68.4	Severely honeycombed
68.4	92.3	Sound concrete
92.3	92.6	Slightly honeycombed
92.6	98.5	Sound concrete
98.5	99.0	Slightly honeycombed

(Continued)

Table A1 (Concluded)

Depth, ft		
From	To	Concrete Description
99.0	107.0	Sound concrete
107.0	107.2	Slightly to moderately honeycombed
107.2	112.1	Sound concrete
112.1	114.7	Severely honeycombed
114.7	115.7	Sand segregation
115.7	116.6	Sound concrete
116.6	118.6	Badly broken and honeycombed - one-half loose aggregate with cement attached
118.6	119.6	Severely honeycombed
119.6	120.0	Sound concrete
120.0	121.4	Severely honeycombed
121.4	128.9	Moderately honeycombed
128.9	158.8	Slightly honeycombed
158.8	188.8	Sound concrete
188.8	189.5	Concrete broken by drill
189.5	191.1	Sound concrete
191.1	191.5	Concrete broken by drill
191.5	212.6	Sound concrete
--	212.6	Bottom of core

Table A2

Summary of Core Log, Element P985 (Primary Element)

Depth, ft		
From	To	Concrete Description
--	1.9	Top of concrete
1.9	2.7	Neat grout grading into sandy grout
2.7	10.5	Concrete with 3/4-in. maximum well rounded quartz aggregate (sound concrete)
10.5	11.5	Vertical seam of uncemented aggregate
11.5	36.6	Sound concrete
36.6	37.1	Severely honeycombed and broken
37.1	38.0	Sound concrete
38.0	38.8	Severely honeycombed
38.8	39.4	Moderately to badly honeycombed
39.4	40.3	Severely honeycombed
40.3	41.8	Sand segregation
41.8	46.3	Severely honeycombed
46.3	69.1	Sand segregation - less than 50 percent of normal aggregate
69.1	90.8	Sound concrete
90.8	91.8	Moderately honeycombed - broken by drill
91.8	93.2	Sand segregation
93.2	94.3	Moderately honeycombed
94.3	96.4	Sound concrete
96.4	96.7	Moderately honeycombed and broken
96.7	100.5	Sound concrete
100.5	104.3	Slight sand segregation
104.3	119.0	Sound concrete
--	119.0	Bottom of hole

Table A3

Summary of Core Log, Element P1001 (Primary Element)

Depth, ft From	To	Concrete Description
--	1.7	Top of concrete
1.7	46.6	Concrete with 3/4-in. maximum well rounded quartz aggregate (sound concrete)
46.6	47.0	One-half of core washed out as sand in drill water
47.0	79.2	Sound concrete
79.2	79.3	Core broken by drill
79.3	80.6	Sound concrete
80.6	80.9	Concrete porous (air bubbles)
80.9	81.4	Sound concrete
81.4	81.6	Concrete porous (air bubbles)
81.6	82.9	Sound concrete
82.9	83.1	Concrete porous (air bubbles)
83.1	91.4	Sound concrete
91.4	91.8	Concrete broken; slightly honeycombed
91.8	96.7	Sound concrete
96.7	99.2	Slight sand segregation
99.2	104.9	Sound concrete
--	104.9	Bottom of hole

Table A4

Summary of Core Log, Element S576 (Secondary Element)

Depth, ft		
From	To	Concrete Description
--	2.5	Top of concrete
2.5	150.0	Concrete with 3/4-in. maximum well rounded quartz aggregate (sound concrete)
150.0	152.6	Sand segregation, solid core
152.6	207.5	Sound concrete
207.5	--	Intercepted limestone

APPENDIX B: TREMIE CONCRETE PLACEMENT LOGS FOR SELECTED ELEMENTS

1. Tables B1 and B2 present samples of tremie concrete placement data sheets as used on this project.

2. Tables B3 through B16 present data on tremie concrete placement for eight primary elements and six secondary elements. These data were derived from the work sheets completed by the Corps Inspector during the placements.

3. The data presented in this appendix are summarized in Table 5 in the text.

Table B1

CONCRETE

SHIFT: 0700-17

...LE NO P-807 DATE: 2 MAR 79 WEATHER: Clear, Mild

...LL TREMIE ...T	FINISH	CONCRETE START	CONCRETE FINISH	DEPTH BOTTOM OF TREMIE	DEPTH TOP OF CONCRETE	VOLUME CONCRETE	WASTE	BATCH NO.	SLUMP
...30	0830	0904	0909	212.4	168	8		1 (124)	
		0914	Break 0917	195	138	8		2 (111)	7"
		10 min. 0927	0930	155	103				
		0936	Break 0939	135 135	79	8		3 (117)	
		10 min. 0950	0953	95	38				
		1005	Break 1007	55	20	5 1/2	1/2	4 (141)	
		5 min. 1012	1015	35	0				
				TOTAL PLACEMENT		29 1/2 CY	1/2		

REMARKS: AT START OF PLACEMENT THE TREMIE PIPE WAS PLACED 0.30 OF... BOTTOM OF THE HOLE. AFTER INJECTING CONCRETE INTO THE TREMIE PIPE F... SEC. THE PIPE WAS RAISED ANOTHER 0.60 TO ALLOW SPHERE ROOM TO ESCAPE. Pipe sphere did not return. Trucks 2, 3 & 4 were broken to ... embedment of tremie less than 65'. No laitance came up with good quality concrete.

EQUIPMENT:

DESCRIPTION	NO.	WORK	IDLE	DOWN
4" Mud Water Pump	1	1		
Ready Mix Trucks	2	2		

PERSONNEL

TYPE EMPLOYEE	NO.
Conc. Spcl.	1
Laborers	2
Operator	1
Teamsters	2

...RYS: BATCH NO.	CONC. TEMP.	WATER	OUTSIDE	INSIDE	TREMIE REMOVED	BOTTOM OF TREMIE	TOP OF CONCRETE
		2.0	168	88		212.4	168
		2.0'	138	67	Removed 18' Tremie	195	138
		2.0'	103	56	Removed 40' Tremie	155	103
		2.0'	79	39	Removed 20' Tremie	135	79
		2.0	38	17	Removed 40' Tremie	95	38
		20	20	11	Removed 40' Tremie	55	20
					Removed 20' Tremie	35	0

Bot of Csg 212.7
Bot of Tremie 212.4
0.3'

INSPECTOR

...ALITY PRACTICABLE
... ... DDC

Table B2

CONCRETE

SHIFT: [illegible]

NO. 5 FSE DATE: 3/6/79 WEATHER: [illegible]

TREMIE FINISH	CONCRETE START	CONCRETE FINISH	DEPTH BOTTOM OF TREMIE	DEPTH TOP OF CONCRETE	VOLUME CONCRETE	WASTE	BATCH NO.	SLUMP	AIR
1115	1104	1109	262.91	243'	8.0	0	1 (101)	—	—
	1110	1115	262'	216	8.0	0	2 (708)	—	—
	1120	1125	235	184	8.0	0	3 (134)	7 1/4"	6 3/4 %
	1133	1138	195	164	8.0	0	4 (119)	—	—
	1143	1148	175	139	8.0	0	5 (114)	—	—
	1153	1158	155'	117	8.0	0	6 (123)	—	—
	1203	1208	135	95'	8.0	0	7 (120)	—	—
	1212	1217	115	74	8.0	0	8 (105)	—	—
	1223	1228	95'	55	8.0	0	9 (102)	—	—
	1233	1239	75'	38'	8.0	0	10 (118)	—	—
	1244	1249	55'	18'	8.0	0	11 (102)	—	—
	1255	1301	35	3	8.0	0	12 (102)	—	—
	1312	1315	15	2	1.0	0	13	—	—
1330			0						—
	Total	CY	<		97.0	0	—	—	—

REMARKS: AT START OF PLACEMENT THE TREMIE PIPE WAS PLACED 0.30 OFF TH[E] BOTTOM OF THE HOLE. AFTER INJECTING CONCRETE INTO THE TREMIE PIPE FOR 60 SEC. THE PIPE WAS RAISED ANOTHER 0.60 TO ALLOW SPHERE ROOM TO ESCAPE.
Pine sphere did not Return - Good concrete Return
no [illegible] on [illegible].

EQUIPMENT: DESCRIPTION	NO.	WORK	IDLE	DOWN
[illegible] 4" pump	1	2.5		
[illegible] Mix Trucks	3	7.5		

PERSONNEL: TYPE EMPLOYEE	NO.	HO[URS]
Concrete Spec	1	6
Laborers	2	12.
Pump Operator	1	2.5
[illegible]	3	7.5

BATCH No	CONC TEMP	[illegible]	[illegible] IN	[illegible]	TREMIE REMOVED	BOTTOM OF TREMIE	TOP OF CONCRETE	[illegible]
		2.6	112'	216'	None	262'	243	2[illegible]
1	53°	3.0'	107'	184'	Remove 20' Tremie	235	216	27
2	[illegible]	3.2	86'	161'	" - 40' "	195	184	[illegible]
3	27°	3.4'	74.5'	139'	" - 20' "	175	161	23
4	[illegible]	3.5	73'	117'	" - 20' "	155	139	2[illegible]
5	34°	2.8'	50'	95'	" - 20' "	135	117	22
6	[illegible]	3.2	34'	74	" - 20' "	115	95	22
7	57°	3.3	27'	55	" - 20' "	95	74	21
8	[illegible]	3.0	19'	38	" - 20' "	75	55	19
9	[illegible]	3.9	8'	18'	" - 20' "	55	38	17
10	54	—	—	—	" - 20' "	35	18	20
11	[illegible]	—			" - 20' "	15	3	
12	57°				Remove all Tremie	0	2	
13								

Bottom of hole 263.20
[illegible] 262.91

INSPECTOR

[illegible] PRACTICABLE
[illegible] DDC

Table B3

Tremie Concrete Placement Data, Element P611

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.5	None	None	171	41.5
2	195	171	24	140	55
3	155	140	15	108	47
4	135	108	27	82	53
5	95	82	13	38	57
6	55	38	17	19	36
7	35	19	16	0	35
Averages	NA	NA	16.5	NA	46.4

Table B4

Tremie Concrete Placement Data, Element P771

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.5	None	None	171	41.5
2	195	171	24	140	55
3	155	140	15	107	48
4	135	107	28	80	55
5	95	80	15	43	52
6	55	43	12	20	35
7	35	20	15	0	35
Averages	NA	NA	18.2	NA	45.9

Table B5

Tremie Concrete Placement Data, Element P773

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.8	None	None	166	46.8
2	195	166	29	139	56
3	155	139	16	109	46
4	135	109	26	80	55
5	95	80	15	40	55
6	55	40	15	16	39
7	35	16	19	0	35
Averages	NA	NA	18.3	NA	47.5

Table B6

Tremie Concrete Placement Data, Element P791

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.6	None	None	169	43.6
2	195	169	26	137	58
3	155	137	18	107	48
4	135	107	28	78	57
5	95	78	17	38	57
6	55	38	17	18	37
7	35	18	17	2	33
Averages	NA	NA	20.5	NA	47.7

Table B7

Tremie Concrete Placement Data, Element P795

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.6	None	None	170	42.6
2	195	170	25	138	57
3	155	138	17	104	51
4	135	104	31	80	55
5	95	80	15	37	58
6	55	37	18	20	35
7	35	20	15	1	34
Averages	NA	NA	20.2	NA	47.5

Table B8

Tremie Concrete Placement Data, Element P807

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.4	None	None	168	44.4
2	195	168	27	138	57
3	155	138	17	103	52
4	135	103	32	79	56
5	95	79	16	38	57
6	55	38	17	20	35
7	35	20	15	0	35
Averages	NA	NA	20.7	NA	48.1

Table B9

Tremie Concrete Placement Data, Element P985

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	172.9	None	None	125	47.9
2	135	125	10	101	34
3	115	101	14	63	52
4	75	63	12	24	51
5	35	24	11	0	35
Averages	NA	NA	14.3	NA	44.0

Table B10

Tremie Concrete Placement Data, Element P1001

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	173.0	None	None	128	45
2	155	128	27	98	57
3	115	98	17	63	52
4	75	63	12	22	53
5	35	22	13	0	35
Averages	NA	NA	17.3	NA	48.4

Table B11

Tremie Concrete Placement Data, Element S576

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.2	None	None	164	48.2
2	175	164	11	141	34
3	155	141	14	117	38
4	135	117	18	92	43
5	115	92	23	65	50
6	75	65	10	43	32
7	55	43	12	20	35
8	35	20	15	2	33
Averages	NA	NA	14.7	NA	39.2

Table B12

Tremie Concrete Placement Data, Element S594

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.3	None	None	164	48.3
2	175	164	11	138	37
3	155	138	17	112	43
4	135	112	23	85	50
5	95	85	10	65	30
6	75	65	10	41	34
7	55	41	14	19	36
8	35	19	16	2	33
Averages	NA	NA	14.4	NA	38.9

Table B13

Tremie Concrete Placement Data, Element S676

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.4	None	None	165	47.4
2	175	165	10	140	35
3	155	140	15	117	38
4	135	117	18	90	45
5	115	90	25	69	46
6	95	69	26	50	45
7	75	50	25	25	50
8	35	25	10	5	30
9	15	5	10	2	13
Averages	NA	NA	17.4	NA	38.8

Table B14

Tremie Concrete Placement Data, Element S746

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	212.6	None	None	168	44.6
2	195	168	27	141	54
3	155	141	14	117	38
4	135	117	18	92	43
5	115	92	23	70	45
6	95	70	25	49	46
7	75	49	26	23	52
8	35	23	12	3.5	31.5
9	15	3.5	11.5	2	13
Averages	NA	NA	19.6	NA	40.8

Table B15

Tremie Concrete Placement Data, Element S858

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	262.9	None	None	216	46.9
2	235	216	19	184	51
3	195	184	11	161	34
4	175	161	14	139	36
5	155	139	16	117	38
6	135	117	18	95	40
7	115	95	20	74	41
8	95	74	21	55	40
9	75	55	20	38	37
10	55	38	17	18	37
11	35	18	17	3	32
12	15	3	12	2	13
Averages	NA	NA	16.8	NA	37.2

Table B16

Tremie Concrete Placement Data, Element S956

Concrete Lift	Tremie Mouth Elevation at Start of Lift ft	Concrete Surface Elevation at Start of Lift ft	Tremie Embedment at Start of Lift ft	Concrete Surface Elevation at End of Lift ft	Tremie Embedment at End of Lift ft
1	172.4	None	None	124	48
2	135	125	11	101	34
3	115	101	14	78	37
4	95	78	17	56	39
5	75	56	19	38	37
6	55	38	17	20	30
7	35	20	15	2	33
Averages	NA	NA	15.5	NA	36.9

APPENDIX C: HYDROSTATIC BALANCE DATA FOR SELECTED ELEMENTS

1. Tables C1 through C6 present hydrostatic balance data for three primary elements and three secondary elements. These data were taken from the work sheets completed by the Corps' Inspector during the placements.

2. The data presented in this appendix are summarized in Table 6 in the text. Tremie pipe geometry and the derivation of the equation used to reduce the data are in Figure 24 of the text.

Table C1

Hydrostatic Balance Data, Element P791

Concrete Lift	Deck To Water ft	Deck To Pipe Tip ft	Deck To Concrete Outside Tremie ft	Deck To Concrete Inside Tremie ft	Total Resistance To Flow lb/ft^2	Contact Length ft	Resistance Per Foot lb/ft
1	2.4	212.6	169	73.6	3433	183	18.8
2	2.5	195	137	72	1017	181	5.6
3	2.4	155	107	57	710	146	4.9
4	2.4	135	78	38.4	1019	154	6.6
5	2.4	95	38	18	677	134	5.1
6	2.4	55	18	2	1353	90	15.0
7	2.0	35	2	0	292	68	4.3

$\gamma_c = 146\ lb/ft^3$

$\gamma_w = 63\ lb/ft^3$

Table C2

Hydrostatic Balance Data, Element P795

Concrete Lift	Deck To Water ft	Deck To Pipe Tip ft	Deck To Concrete Outside Tremie ft	Deck To Concrete Inside Tremie ft	Total Resistance To Flow lb/ft^2	Contact Length ft	Resistance Per Foot lb/ft
1	1	212.6	170	78	2785	177	15.7
2	1	195	138	72	1005	180	5.6
3	1	155	104	56	519	150	3.5
4	1	135	80	36	1447	154	9.4
5	1	95	37	16	798	137	5.8
6	1	55	20	6	847	84	10.1
7	1	35	1	0	146	69	2.1

$\gamma_c = 146\ lb/ft^3$

$\gamma_w = 63\ lb/ft^3$

Table C3

Hydrostatic Balance Data, Element P807

Concrete Lift	Deck To Water ft	Deck To Pipe Tip ft	Deck To Concrete Outside Tremie ft	Deck To Concrete Inside Tremie ft	Total Resistance To Flow lb/ft^2	Contact Length ft	Resistance Per Foot lb/ft
1	2	212.4	168	88	1222	169	7.2
2	2	195	138	67	1798	185	9.7
3	2	155	103	56	499	151	3.3
4	2	135	79	39	989	152	6.5
5	2	95	38	17	798	135	5.9
6	2	55	20	11	180	79	2.3

$\gamma_c = 146\ lb/ft^3$

$\gamma_w = 63\ lb/ft^3$

Table C4

Hydrostatic Balance Data, Element S746

Concrete Lift	Deck To Water ft	Deck To Pipe Tip ft	Deck To Concrete Outside Tremie ft	Deck To Concrete Inside Tremie ft	Total Resistance To Flow lb/ft^2	Contact Length ft	Resistance Per Foot lb/ft
1	2.2	212	168	86	1195	170	7.0
2	2.1	195	141	67	1776	182	9.8
3	1.8	155	117	57	1272	136	9.4
4	2.0	135	92	45	1012	133	7.6
5	3.0	115	70	33	1047	127	8.2
6	2.4	95	49	21	1059	120	8.8
7	3.2	75	23	9.5	684	118	5.8
8	3.5	35	3.5	-1.0	657	68	9.7

$\gamma_c = 146\ lb/ft^3$

$\gamma_w = 65\ lb/ft^3$

Table C5

Hydrostatic Balance Data, Element S858

Concrete Lift	Deck To Water ft	Deck To Pipe Tip ft	Deck To Concrete Outside Tremie ft	Deck To Concrete Inside Tremie ft	Total Resistance To Flow lb/ft^2	Contact Length ft	Resistance Per Foot lb/ft
1	2.6	262.9	216	112	1313	198	6.6
2	3.0	235	184	107	-523	179	-2.9
3	3.2	195	161	86	693	143	4.8
4	3.4	175	139	74.5	603	137	4.4
5	3.5	155	117	73	-954	120	-7.9
6	2.8	135	95	50	577	125	4.6
7	3.2	115	74	34	1238	122	10.1
8	3.3	95	55	27	728	108	6.7
9	3.0	75	38	19	499	93	5.4
10	3.9	55	18	8	544	84	6.5

$\gamma_c = 146\ lb/ft^3$

$\gamma_w = 65\ lb/ft^3$

Table C6

Hydrostatic Balance Data, Element S956

Concrete Lift	Deck To Water ft	Deck To Pipe Tip ft	Deck To Concrete Outside Tremie ft	Deck To Concrete Inside Tremie ft	Total Resistance To Flow lb/ft^2	Contact Length ft	Resistance Per Foot lb/ft
1	3.0	172	124	64.2	866	156	5.6
2	3.4	135	101	50.5	1029	119	8.9
3	3.5	115	78	37	1144	115	9.9
4	3.4	95	56	27	815	107	7.6
5	3.2	75	38	18	658	94	7.0
6	3.6	55	20	8.5	613	82	7.5

APPENDIX D: EXCERPTS FROM WOLF CREEK CONCRETE SPECIFICATIONS

Following are sections of the concrete specification used at Wolf Creek which deal with tremie placement.

6-9. PROPORTIONING OF CONCRETE.

6-9.1 Control.--The proportions of all material entering into the concrete shall be as approved. The proportions shall be changed as necessary to maintain the required quality. Adjustments shall be made to the batch weights of cement and water as necessary to maintain the water-cement ratio and the stipulated slump with approval of the Contracting Officer. The concrete mixture shall be proportioned and mixed for a minimum 28 day compressive strength of 3,000 pounds per square inch in accordance with CRD-C 14.

6-9.2 Cement Content.--The total content of cementitious material shall be approximately 675 pounds per cubic yard. Pozzolan shall constitute 20% of absolute volume of the total cementing material. Cement content will vary as required to meet the specified quality.

6-9.3 Aggregate Content.--Fine aggregate should constitute approximately 45% of the total aggregate. The maximum size of coarse aggregate to be used will be 3/4 inches.

6-9.4 Air Content.--The air content by volume based on measurements made immediately after discharge from the mixer shall be determined by ASTM C 231. The total calculated air content shall be 6.0 ± 1.5 percent.

6-9.5 Slump.--For each portion of the work the slump shall be between 6 and 7-1/2 inches when measured by ASTM C 143.

6-12. PLACING BY TREMIE METHOD.

6-12.1 General.--Concrete for the diaphragm wall shall be placed in a stabilizing fluid filled element by a tremie in such a manner that the concrete displaces the stabilizing fluid. The methods and equipment used shall be subject to approval. Concrete buckets will not be permitted for the placement of concrete in the diaphragm wall elements. The tremie shall be watertight. The tremie seal shall be effected in a manner which will not produce undue turbulance in the stabilizing fluid around the

pipe. The discharge end shall be kept submerged continuously in the fresh concrete to eliminate washing, segregation, and/or contamination of the concrete. The tremie shall be kept full of concrete to a point well above the concrete surface. Placement shall proceed without interruption until the concrete has been brought to the required height. The Contractor may be required to use a Government-furnished dye in certain batches of concrete.

6-12.2 Tremie and Holding Hopper.--The tremie shall be 10 inches in diameter for 3/4 inch size coarse aggregate and may be sectioned in removable lengths. Watertight, quick-disconnect couplers shall be required for joining the lengths of sectioned tremies. A traveling plug (Go Devil) shall be required to start each placement and shall be subject to the approval of the Contracting Officer. A funnel shaped holding hopper of at least 1/2 cubic yard in volume shall be required at the top of the tremie. Hoisting equipment shall be continuously available for raising and lowering the tremie pipe as the concrete is being placed. Aluminum shall not be permitted for the tremie pipe or holding hopper.

6-12.3 Placement.--The concreting operation shall follow the recommended practice for measuring, mixing, transporting and placing concrete as recommended in ACI Standard 304-73. Placement of tremie concrete is discussed in Chapter 8 of the above publication. The tremie shall be lowered to rest on the bottom of the element and slowly raised to start the flow of concrete. The tremie shall be kept submerged continuously in the fresh concrete depending on the rate of flow and the head of concrete in the tremie pipe. The depth of concrete in the tremie shall be sufficient to balance the stabilizing fluid head and maintain flow. The Contractor shall be required to make continuous sounding of the concrete surface for the necessary control. The conveyance of concrete to the holding hopper shall be at a near continuous flow, and batches of concrete shall not be dumped suddenly into the holding hopper. Delays in placement of over 30 minutes will not be permitted. The elements shall be overfilled so that all concrete containing laitances, scum and other contaminants can be removed and wasted in an approved disposal area.

6-12.4 Plugs, Loss of Seal, Resealing and Inspection.--Plugs may be best freed by quickly raising the tremie a few inches at a time to avoid loss of seal. Should loss of seal occur, the Contractor shall use a non-buoyant gasketed plate, valved, or other approved tremie so as to obtain reseal without contamination of the concrete with stabilizing fluid. The Contractor will be required to extract a drill core of hardened concrete from the top of an element to at least 25 feet below the location of all losses

of seal to allow the Contracting Officer to determine the integrity of an element. This drilling shall be performed as specified in Section 6-13.7.1 and at no additional cost to the Government. Unacceptable zones of concrete shall be repaired by approved methods. The Contractor shall submit a proposal to cover repair of unacceptable in place concrete.

6-12.5 Time Interval Between Mixing and Placing.--Concrete mixed in stationary mixers and transported by non-agitating equipment shall be placed within 30 minutes after it has been mixed, unless otherwise authorized. When concrete is truck-mixed or when a truck mixer or agitator is used for transporting concrete mixed by stationary mixers, the concrete shall be delivered to the site of the work and discharges shall be completed within 45 minutes after introduction of the cement to the aggregate except that when the temperature of the concrete exceeds 85 degrees F. the time shall be reduced 30 minutes. The concrete shall be placed within 15 minutes after it has been discharged.

6-12.6 Placing Temperatures.--Concrete, when deposited in the wall, shall have a temperature of not less than 40°F. Heating of the mixing water or aggregates will not be permitted until the temperature of the concrete has decreased to 45°F. The materials shall be free from ice, snow, and frozen lumps before entering the mixer. All methods and equipment shall be subject to approval. When heating is necessary to keep the concrete temperature above 40°F, it shall be regulated so that the concrete temperature does not exceed 60°F.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Holland, Terence C

Construction of tremie concrete cutoff wall, Wolf Creek Dam, Kentucky / by Terence C. Holland, Joseph R. Turner. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1980.

48, [40] p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; SL-80-10)

Prepared for Office, Chief of Engineers, U. S. Army Washington, D. C., under CWIS 31553.

References: p. 48.

1. Concrete placing. 2. Cutoff walls. 3. Diaphragm wall construction. 4. Earth dams. 5. Tremie concrete. 6. Underwater construction. 7. Wolf Creek Dam. I. Turner, Joseph R., joint author. II. United States. Army. Corps of Engineers. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; SL-80-10.

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